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Core mechanisms in 'theory of mind'

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Our ability to understand the thoughts and feelings of other people does not initially develop as a theory but as a mechanism. The 'theory of mind' mechanism (ToMM) is part of the core architecture of the human brain, and is specialized for learning about mental states. Impaired development of this mechanism can have drastic effects on social learning, seen most strikingly in the autistic spectrum disorders. ToMM kick-starts belief–desire attribution but effective reasoning about belief contents depends on a process of selection by inhibition. This selection process (SP) develops slowly through the preschool period and well beyond. By modeling the ToMM-SP as mechanisms of selective attention, we have uncovered new empirical phenomena. We propose that early 'theory of mind' is a modular–heuristic process of domain-specific learning.

Attributing thoughts and goals to others, the ability we call 'theory of mind' [1], is central to our social life. Two decades of intensive research show that reasoning about beliefs and desires begins very early – in infancy and preschool age. Yet belief and desire are among the most abstract entities we ever think about. So these findings deeply challenge entrenched assumptions about the nature of mind and the origins of representation. One response to this challenge has been to suppose that we are born as 'little scientists' who discover belief and desire through experimentation, observation and theory-building [2–5]. However, although the effects of many other abstract entities, like Newton's laws of motion, electrons or the genetic code, are observable every hour of every day, preschoolers never discover them. Another response to the challenge is to suppose that the belief and desire concepts are innate. But this raises the challenge of explaining *how*: How can these concepts be innate? Our proposal is that the concepts are introduced into the cognitive system by a mechanism, analogously to the way that color concepts are introduced by the mechanisms of color vision. The child does not build theories of what color is nor discover theories of particular colors. Instead the mechanisms of color vision serve to introduce color representations and to lock the representations to appropriate referents in the world. In this vein, our research agenda is to investigate and characterize the core inferential mechanisms of belief–desire reasoning.

Early belief–desire reasoning has been investigated through the false-belief task and its variants [6,7]. Children are told a story in which Sally places a marble in a basket. Anne then moves the marble to a box while Sally is absent. Children are asked where Sally will look for her marble when she returns (action prediction) or simply where Sally thinks her marble is (belief). Normally developing children as young as 4 years typically pass such tasks, whereas children younger than 4 and much older children with autism typically fail. A second reason for investigating mechanisms of belief–desire reasoning is to provide an information-processing account of successful performance. If we are right, one account will do two jobs: provide a processing account of early belief–desire reasoning and explain the origins of concepts about mental states.

We will describe two models and some recent data that informs the choice between them. We then reflect upon the nature of basic 'theory of mind' and the origins of early abstract ideas.

Two models of early belief–desire reasoning

To date, two processing models of belief–desire reasoning have been detailed [8,9]. The models share three principle features. First, they assume a representational system powerful enough to represent beliefs and desires *as such*. We call this system, the 'metarepresentation', and believe it is introduced by a specialized neurocognitive 'theory-of-mind mechanism' (ToMM) [10,11]. Second, the models assume that successful reasoning with belief and desire metarepresentations recruits an inhibitory selection process (SP). Third, because people's mundane beliefs are usually true, the best guess about another person's belief is that it is the same as one's own. Let us call this the true-belief default. The false-belief task presents one situation where the default fails; to succeed, the attributer must inhibit the true-belief default so that a belief with another content can be selected. The ToMM can provide other candidate contents in addition to the true-belief: for example, in the Sally–Anne task, the ToMM can provide a content that reflects where Sally last saw the marble. We can visualize the process of selection as involving a mental pointer of attention, which gets attracted to the most salient content. Salience can vary by degree and is decreased by inhibition. Initially, the true-belief content is most salient, and, unless effectively inhibited, will be selected. Preschoolers' ability to apply inhibitions effectively is limited and improves only gradually [12,13].

To predict Sally's action, children must consider both her belief and her desire. In the standard task, Sally desires to approach the marble. A variation on this story,

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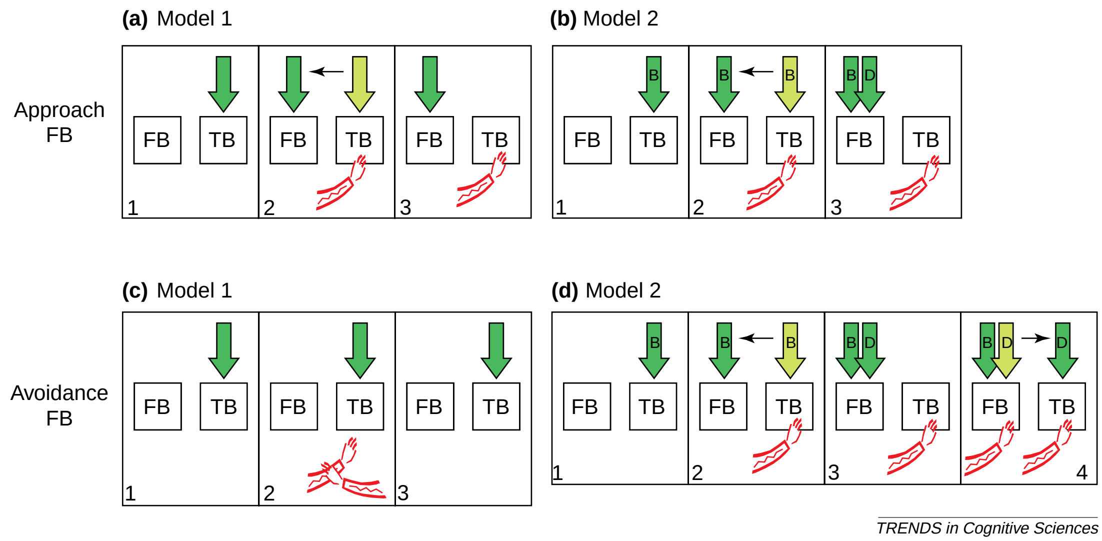

Figure 1. Two competing models of 'selection by inhibition' in belief–desire reasoning. **(a,b)** show how the models operate in the standard false-belief task where the character has a desire to approach the target. For example, Sally might have a true belief (TB) about the location of the marble ('it is in the right-hand box'), or she might have a false belief (FB) about its location ('it is in the left-hand box'). In both models, the TB is initially more salient than the FB and attracts a 'pointer' or attentional index, shown as a green arrow. Then, a belief inhibition, shown as a red arm, is applied to the TB, reducing its salience, and causing the index to move to the FB. For this task, the only difference between the models is that Model 2 has a separate index for belief (labeled B) and desire (labeled D). The desire index is introduced after the belief index and is attracted to the now more salient FB. In both models there are no further inhibitions in this task, so the character's predicted action is to approach the FB location. **(c,d)** show how the models operate for avoidance false-belief tasks where two inhibitions are required. Again, TB is initially more salient and is indexed first. In Model 1, the inhibitions for false belief and avoidance desire are generated in parallel and in such a way that they inhibit each other (cancel out). Because no inhibition reaches the TB, it remains indexed and provides the correct prediction. In Model 2, the TB is inhibited by the false-belief inhibition causing the belief index B to shift to the FB. FB then attracts the desire index D, which is subsequently inhibited for avoidance, forcing the D index to shift back to the still inhibited TB.

in which Sally has a desire to avoid rather than to approach, has proven useful for probing the process of selection by inhibition. There are two boxes but Sally does not want to put a piece of fish into the box where there is a sick kitten. To predict which box Sally will approach, one must first identify the box with the kitten then select the other box. According to our models, predicting action from an avoidance desire also involves a process of selection by inhibition. First, the box with the kitten is indexed as the to-be-avoided target, then inhibited so that the index shifts to the other, to-be-approached, box. When a task combines an avoidance desire with a false belief, two inhibitions will be required.

Thus, in the standard approach-false-belief tasks, predicting a character's behavior requires one inhibition, whereas in avoidance false-belief tasks two inhibitions are required. The models differ from one another in three main respects: first, in whether selection is done serially or in parallel; second, in how many indexes are used; and third, when predicting action in an avoidance FB task, in how the desire and belief inhibitions combine.

In Model 1, 'inhibition of inhibition', there is only a single index and inhibitions are applied in parallel (Figure 1a,c). When predicting where Sally will go in an avoidance false-belief task, the target of true-belief (and approach desire) – the true-belief (TB)-location – is indexed first (Figure 1c). Then the belief and desire inhibitions are applied at the same time such that they cancel each other, hence inhibition of inhibition. The end result is that the TB-location remains indexed, and is selected as the location where Sally will go. This is the correct answer. Notice that if both inhibitions were simply applied to the true-belief content, that is, summed, then the wrong answer would be selected.

In Model 2, 'inhibition of return', two indexes are used, one for belief and one for desire. Indexes and inhibitions are applied serially, with belief indexes/inhibitions applied first and desire indexes/inhibitions second. For standard tasks, Model 2 is similar to Model 1 (Figure 1b). To predict where Sally will go in an avoidance FB task, the target of true belief is again initially indexed (Figure 1d). Because Sally's belief is false, the first of the serial inhibitions is applied, causing the belief index to move to the false-belief (FB)-location. Next, the target of desire is identified, with its index attracted to the FB-location (because it is now more salient). However, because Sally's desire is to avoid the target, a desire inhibition is now applied, lowering the salience of the FB-location so that the index returns to the previously inhibited TB-location.

Testing between models

We have recently discovered new phenomena that support one model and not the other [9,14–16]. Our data for children up to 8 years rule out Model 2 and support Model 1 [15]. In approach-FB tasks, think and prediction questions have the same correct answer (FB-location) and are equally difficult. In avoidance-FB tasks, the correct answer to the prediction question is the TB-location and children find this much more difficult than the think question [8,17]. Only about 35% of 4- and 5-year-old standard-FB passers correctly predict behavior in avoidance-FB.

Two sets of experiments have tested between the models. The first test concerns predictions about whether certain task manipulations should improve prediction in avoidance-FB. The performance of 3-year-olds on standard-FB improves when the prediction question

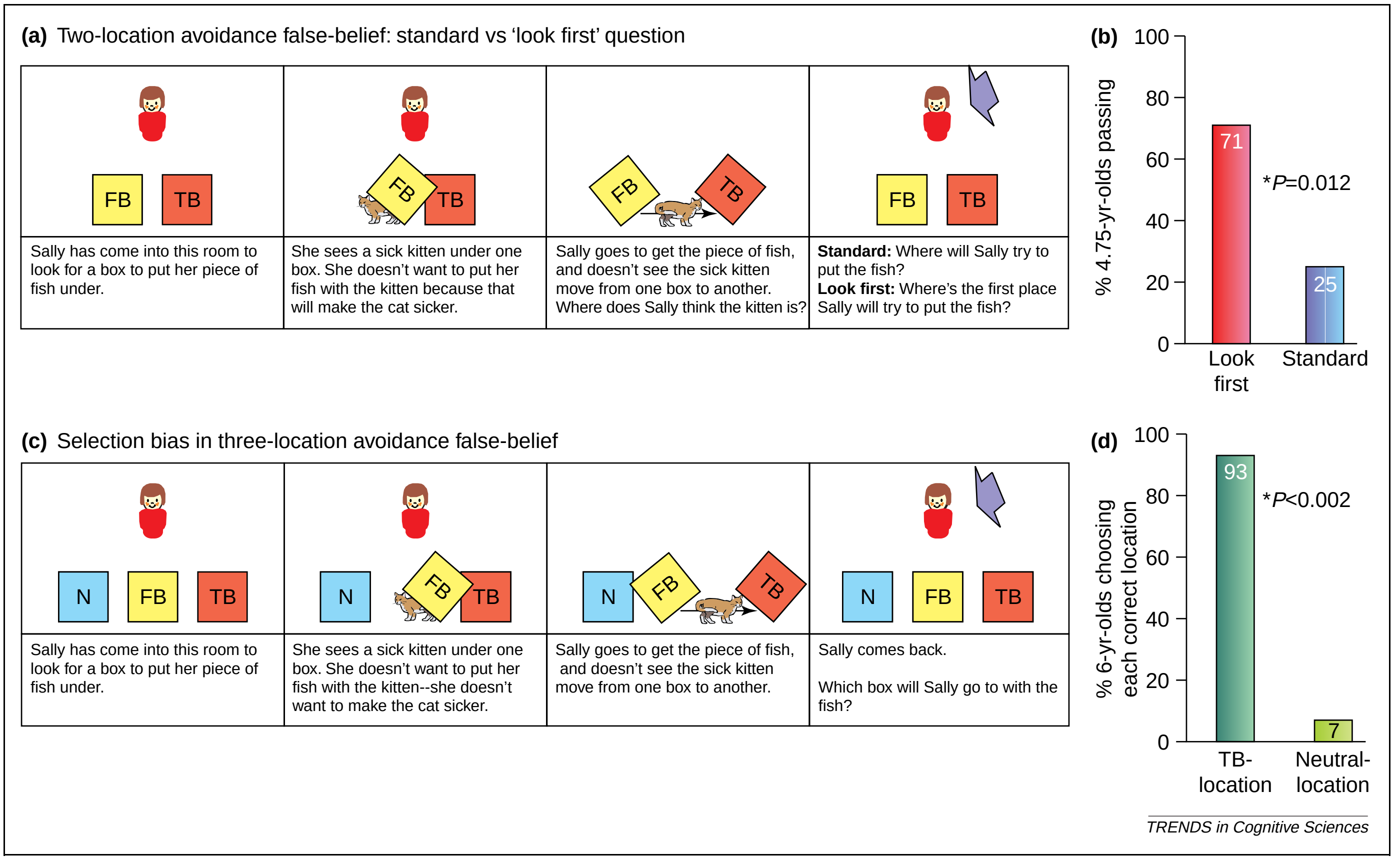

Figure 2. An avoidance false-belief task with a standard prediction question **(a)** is passed by only a fraction (25%) of those four-year-olds who pass an approach false-belief task. If the question is modified slightly to a 'look first' format, most four-year-olds again pass **(b)**. An avoidance false-belief task with a third neutral (N) location has two equally correct answers **(c)**. Six-year-olds who pass a two-location avoidance false-belief task show a strong bias to choose one of the correct answers in a three-location task. They overwhelmingly choose the true-belief (TB) location **(d)**, as predicted by the inhibition-of-inhibition model (Model 1).

asks where Sally will look *first* [18,19]. The word 'first' could increase the salience of the FB-location, thereby reducing the inhibition required to select it [18].

Should a 'look first' question likewise improve performance in the avoidance-FB task? Suppose a child has already correctly answered a think question just before we ask the 'look first' question (Figure 2a,b). Model 1 identifies belief and desire together, in parallel. So although it has calculated belief already, to answer the prediction question the model must recalculate belief along with desire. This gives the 'look first' question an opportunity to work. Model 1 therefore predicts that a 'look first' avoidance FB task will be easier. Model 2 operates serially. By answering (correctly) the think question, Model 2 completes the first of its steps. When we ask the 'look first' question, Model 2 completes its second step by simply adding desire to the already selected belief. However, re-use of the belief answer deprives the 'look first' question of an opportunity to help. Therefore, Model 2 predicts that the 'look first' question will not help 4-year-olds pass avoidance FB. Our experiments show that 'look first' *does* help under these circumstances [9], supporting Model 1 over Model 2.

A second way to test the models is to add a third 'neutral' (N) location to the avoidance false-belief task (Figure 2c,d). With three locations, the task has two equally correct answers: in seeking to avoid the FB-location, Sally can validly go to either the TB- or N-locations. A child can pass by choosing both locations or by choosing one or other randomly. Both models predict that the child will select a particular answer (i.e. be biased). Model 1 predicts that children will select the TB-location: inhibitions for belief and desire occur in parallel and cancel out, leaving the TB-location most salient (Figure 3a). Model 2 predicts that children will select the N-location because in the end that is the only target that is uninhibited (Figure 3b). The models thus predict opposite biases.

Children aged between 4 and 8 years have been tested on several versions of the three-location task, and show a strong bias to select the TB-location over the N-location, again supporting Model 1 over Model 2 [14,15]. By contrast, adults show the opposite (Model 2) bias [15]. There are therefore several developmental shifts in selection processing: from 3–4 years (standard tasks solved), 5–6 years (avoidance tasks solved), and a late shift after 8 years to adult performance.

For 'theory-theorists', the shift from 3–4 years is evidence of a change in conceptual theory with only a minor role at most for processing factors [4]. However, growth in processing resources alone can easily account for this *and* the later shifts. It is also hard to see a role for 'simulation' in accounting for this data. Simulation theory postulates that I understand you by figuring out what I would do, think and feel in your situation and then attribute the result to you [20]. However, the mechanisms

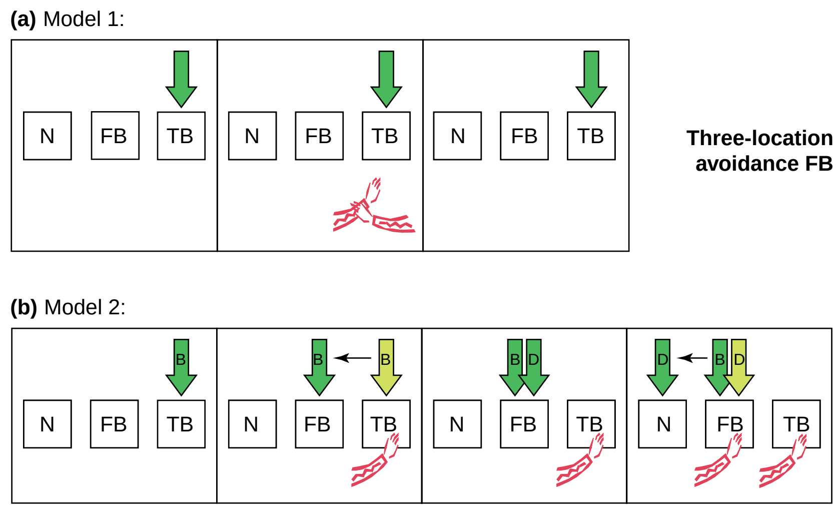

Figure 3. Models 1 and 2 make different predictions for an avoidance false-belief task with three-locations. In this task, there are two equally correct answers to where a character will go to avoid FB, where they mistakenly believe that there is an object to be avoided. Therefore, successful subjects might choose either of the two remaining locations or both of them as their prediction for where the character will go. However, our models predict that subjects will be biased to choose one of the answers over the other. **(a)** For Model 1, the introduction of a third location makes no difference to how it operates. Because this is an avoidance desire false-belief task, two inhibitions are generated in parallel and inhibit each other. No inhibition reaches TB which therefore remains indexed. Subjects should therefore predict that the character will go to the TB-location and not the neutral location (N). **(b)** For Model 2, the introduction of the third location means that the desire index D does not have to return to the still-inhibited TB-location. It will instead be attracted to the uninhibited N-location, as shown in the final frame. Subjects should therefore be biased to predict that the character will go to the N-location. In fact, children tested between 4 and 8 years show a strong Model 1 type bias. Model 2 is therefore ruled out.

of 'theory of mind' might simply figure out what *one* would do, think and feel in a given situation. If pronouns are in fact involved, there is currently no evidence that it is the first-person singular.

'Theory of mind' as heuristic

The Model 1 version of the ToMM-SP theory can account in detail for early 'theory of mind' [9]. Here we summarize the fundamentals of the theory. ToMM may be modular [21], but SP appears to be penetrable to knowledge and instruction [9]. Both mechanisms develop, but SP is an especially important site of development because, early on, the inhibitory powers of SP are largely ineffective.

ToMM and SP together embody basic heuristic principles of theory of mind, so the child does not need to represent these as conceptual statements ('theories'). For example, the principle that people act to satisfy their desires in the light of their beliefs is represented implicitly in ToMM-SP's mode of operation. Further properties of this mode of operation that have been investigated and supported [8,9,16] are that it can:

(a) provide candidate contents for belief attributions

(b) assign initial salience/confidence levels to candidate contents, with highest level to true-belief

(c) review and adjust initial levels in light of specific circumstances

(d) following review, select highest valued candidate.

Given this mode of operation, an account of early developmental change in reasoning about beliefs can be simple: namely, step (c) becomes more capable. One way in which step (c) becomes more capable is by accessing an increasing database of circumstances. A second way is through increasing inhibitory resources. Young children have severely limited inhibitory executive control [12,13,22,23]. Inhibitory control measures correlate with performance on the standard false-belief task [24–27]. Three-year-olds fail because they do not effectively inhibit the default true-belief attribution. False-belief situations, both natural and experimental, will typically appear to them as true-belief situations. For these children, false-beliefs, although hard, are nevertheless already conceivable. This means, crucially, that the door to learning is open.

'Theory of mind' as core architecture

Theory of mind is part of our social instinct, the product of core architecture for specialized learning. The fundamental design problem for a young brain that learns about invisible, intangible, abstract states like belief is being able to attend to such states in the first place [28]. Without noticing these states, the brain could not learn about them. On current evidence, the earliest processes that represent propositional attitudes appear during the second year of life as ToMM comes on-line. ToMM deploys the metarepresentational system [10], introducing concepts like BELIEVE, DESIRE, and PRETEND, and grounding their meaning (reference) by its mode of operation. Any 'theorizing' comes later. The fundamental design specification for ToMM is: permit, promote and direct attention to these states to learn about them.

Recent evidence suggests that children even younger than 3 years solve false-belief tasks when non-verbal measures are used. Young preschool children will look at where the character thinks the target item is, even as they subsequently answer with its real location when asked where the character will look [29,30]. The eyes tacitly give the correct answer although the mouth spouts the wrong answer. Onishi and Baillargeon (unpublished data) have gone further using completely non-verbal tasks. Infants of 15 months of age show looking-time patterns that are consistent with attributing beliefs to agents, including true- and false-beliefs appropriate to the scenario viewed. Infants look longer when the actor searches in the true-belief location in false-belief scenarios and when the actor searches in the false-belief location in true-belief scenarios, the pattern predicted by the violation-of-expectation paradigm [31]. These findings underline the early role of ToMM as a core mechanism of attention, identifying learning opportunities as expectations are violated and directing attention to relevant sources of information (see Box 1).

Could SP, and not ToMM, be the source of the true-belief default? SP is a non-modular, penetrable mechanism whose decisions can heavily influence voluntary behavior, such as talking and pointing. In reaching its decisions, SP accesses a learned database of circumstances relevant to selecting between candidate beliefs. An intriguing possibility is that, sometime between 15 and 30 months, SP *learns* to make the true-belief attribution the default – perhaps, as Onishi and Baillargeon suggest, by coming to discount an agent's lack of perceptual access. The child will encounter many occasions in which adults know things they have apparently not witnessed. Perhaps one task for SP is to learn about circumstances in which lack of access can be trusted. (See Box 2 for other questions for future research.)

Finally, ToMM-SP is consistent with neuroimaging results showing medial frontal cortex, especially the anterior paracingulate, as critically involved in selective belief–desire reasoning [32,33]. In this light, the distinctive social impairments of children with autism result, not from impaired high-level 'intellectual' theory-building, but from impairment to a basic instinct.

Box 1. 'Theory of mind' as a mechanism of selective attention

Attention is nowadays usually thought of as *visual* attention. But an older sense also related it to thought. James wrote 'attention is…the taking possession by the mind…of one out of…several simultaneously possible…trains of thought.' ([34] p. 403). The computational problems of thought-level selective attention might be similar to those at the vision level. The brain could have evolved solutions to higher-level problems by replicating, with modification [35], circuits for visual attention. In our models, attention has polarity – it can be negative as well as positive – with the allocation of attention shifting accordingly. Negative attention is not the same as absence of attention and has its own specific effects. For example, shifting visual attention from one target to another requires inhibition of the initially attended target [36,37] and produces 'inhibition of return' – resistance to the return of attention to a previously inhibited target [38]. Further examples of negative visual attention are negative priming – a target is harder to detect on a subsequent trial if it had to be ignored on a previous trial [39,40], and visual marking – attention to the location of distractors can be voluntarily inhibited to enhance detection of later appearing targets [41]. Interestingly, visual marking can be switched off by other visual processes [42], providing a visual parallel to our 'inhibition of inhibition'. Attentional processes in vision and in reasoning could have interesting and largely unexplored similarities.

Box 2. Questions for future research

- Why does Model 1 and not Model 2 capture children's performance on belief–desire reasoning? Does using only one index and operating in parallel make Model 1 computationally simpler?
- Does Model 2 really capture adult heuristic belief–desire reasoning or is there another explanation for adult's Model 2 bias in the three-location avoidance task?
- When exactly does the shift from Model 1 to Model 2-like processing occur? Is it around puberty? What underlies this shift?
- How are inhibitions triggered in selection processing?
- Is the selection process (SP) simply a domain-general executive process or is SP dedicated to 'theory of mind'? To what extent are frontal executive processes domain-specific?

Summary

Highly abstract 'theory of mind' concepts appear very early in life when general knowledge and reasoning powers are severely limited. They are the result of processing mechanisms specialized for establishing and maintaining the reference of the concepts. Modular processes that promote attention to mental states and facilitate learning about them appear very early and develop rapidly. However, the heuristic processes that select appropriate contents for mental states have a very lengthy development and undergo several major changes. We have modeled these processes as selection by inhibition. By proposing and testing competing models we have uncovered new phenomena in domain-specific learning. These suggest that we should be thinking much less about child 'theories' and much more about mechanisms.

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