

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 mind/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. The selection process (SP) develops slowly through the preschool period and well beyond. By modeling ToMM-SP as mechanisms of selective attention, we uncovered new empirical phenomena. 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 infants and preschoolers. 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 ‘little scientists’ who discover belief and desire through experimentation, observation, and theory-building. [2, 3, 4, 5] However, though the effects of many other abstract entities, like Newton’s laws of motion, electrons or DNA, 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 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. Normally developing children as young as four years typically pass such tasks, whereas 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 mental state concepts.

We will describe two models and some recent data that chooses 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. Call this the *true-belief default*. The false belief task presents one situation where the default fails; to succeed, the attributer must inhibit the default true-belief so that a belief with another content can be selected. The ToMM can provide other candidate contents in addition to the true-belief: e.g., in the Sally-Anne task, ToMM can provide a content reflecting where Sally last saw the marble. In Figures 1 and 2 the process of selection is visualized 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, 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 sits 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 desire 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.

In standard approach false-belief tasks, predicting a character’s behavior requires one inhibition; 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 (Fig. 1, top left panel). 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. 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 (Fig. 1, bottom left panel). 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 (Fig. 1, top right panel). To predict where Sally will go in an avoidance FB task, the target of true belief is again initially indexed. 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 (Fig. 1, bottom right panel).

Figure 1 about here

Testing between models

We have discovered new phenomena that support one model and rule out the other [9, 14,15, 16]. Our data for children up to eight 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 four- and five-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. Three-year-old’s performance on standard FB improves when the prediction question asks where Sally will look *first*. [18, 19] The word ‘first’ may work by increasing 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 2, top panels). Model 1 identifies belief and desire together, *in parallel*. So although it has calculated belief already, to answer prediction 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 four-year-olds pass avoidance FB. Studies show that ‘look first’ *does* help under these circumstances [9], supporting Model 1 over Model 2.

Figure 2 about here

A second way to test the models is to add a third ‘Neutral’ location to the avoidance false belief task (Fig. 2, bottom panels). With three locations, the task has two equally correct answers: in seeking to avoid the FB-Location, Sally may validly go to either the TB- or Neutral-

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 (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 (Fig. 3, top panel). Model 2 predicts that children will select the Neutral-Location because in the end that is the only target that is uninhibited (Fig. 3 bottom panel). The models thus predict opposite biases.

Figure 3 about here

Children aged between 4 and 8 years have been tested on several versions of the three location task. Children are heavily biased to select the TB-Location over the Neutral-Location, again supporting Model 1 over Model 2 [14, 15]. Adults, by contrast, do not show the opposite (Model 2) bias [15]. There are therefore a number of developmental shifts in selection processing: from 3-4 years (standard tasks solved), 5-6 years (avoidance tasks solved), and a late post-8 years shift to adult performance.

For ‘theory-theorists,’ the shift from 3-4 years is evidence of conceptual theory change 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/feel in *your* situation and then attribute the result to you [20]. However, the mechanisms of ‘theory of mind’ may simply figure out what *one* would do/think/feel in given situation. If pronouns are in fact involved, there is currently no evidence that it is 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 some basics. 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+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 a gloss on ToMM-SP’s mode of operation (MO). Further properties of this MO that have been investigated and supported [8, 9, 16] are:

- (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 MO, 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, 25, 26, 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, though hard, are *conceivable*: 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 MO. Any ‘theorizing’ comes later. The fundamental design spec for ToMM is: permit, promote, and direct attention to these states in order to learn about them.

Recent evidence suggests that children younger even than three years solve false-belief tasks when non-verbal measures are used. Young preschoolers 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 while the mouth spouts the wrong answer. Onishi and Baillargeon (unpublished) have gone further with completely non-verbal tasks. Fifteen-month-olds show looking-time patterns 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).

Box 1 about here

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, like 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 *is* to be trusted.

Finally, ToMM-SP is consistent with neuro-imaging results showing medial frontal, 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.

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 a number of major changes. We have modeled these processes as selection by inhibition. By proposing and testing competing models we uncovered new phenomena in domain specific learning. We should be thinking much less about child “theories” and much more about mechanisms.

Attention is nowadays 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.” (p. 403).^a The computational problems of thought-level selective attention may be similar to those at the vision level. The brain may have evolved solutions to higher level problems by replicating-with-modification^b 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^{c,d} and produces *inhibition of return* — resistance to the return of attention to a previously inhibited target.^e 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,^{f,g} and *visual marking* — attention to the location of distractors can be voluntarily inhibited to enhance detection of later appearing targets.^h Interestingly, visual marking can be switched off by other visual processes,ⁱ providing a visual parallel to our ‘inhibition of inhibition’. Attentional processes in vision and in reasoning may have interesting and largely unexplored similarities.

^a James, W. (1890). *Principles of psychology*. New York, NY: Henry Holt.

^b Maynard Smith, J., & Szathmáry, E. (1997). *The major transitions in evolution*. New York, NY: Oxford University Press.

^c Posner, M.I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention and Performance, X* (pp. 531–556). Hillsdale, NJ: Erlbaum.

^d Rafal, R., & Henik, A. (1994). The neurology of inhibition: Integrating controlled and automatic processes. In D. Dagenbach and T.H. Carr (Eds.), *Inhibitory processes in attention, memory and language*. (pp. 1–51.) New York: Academic Press.

^e Posner, M.I., Rafal, R.D., Choate, L.S., Vaughan, J. (1985). Inhibition of return: Neural basis and function. *Cognitive Neuropsychology*, **2**, 211–228.

^f Allport, D.A., Tipper, S.P., & Chmiel, N.R.J. (1985). Perceptual integration and postcategorical filtering. In M.I. Posner and O.S.M. Marin (Eds.), *Attention and performance XI*. (pp. 107–132). Hillsdale, NJ: Erlbaum.

^g Tipper, S.P., & Driver, J. (1988). Negative priming between response modalities: Evidence for the central locus of inhibition. *Perception & Psychophysics*, **43**, 45–52.

^h Watson, D.G., & Humphreys, G.W. (2000). Visual marking: Evidence for inhibition using a probe-dot detection paradigm. *Perception & Psychophysics*, **62**, 471–481.

ⁱ Watson, D.G., & Humphreys, G.W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review*, **104**, 90–122.

Box 1. “Theory of mind” as a mechanism of selective attention.

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 3-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 SP simply a domain general executive process or is SP dedicated to 'theory of mind'? To what extent are frontal executive processes domain dedicated?

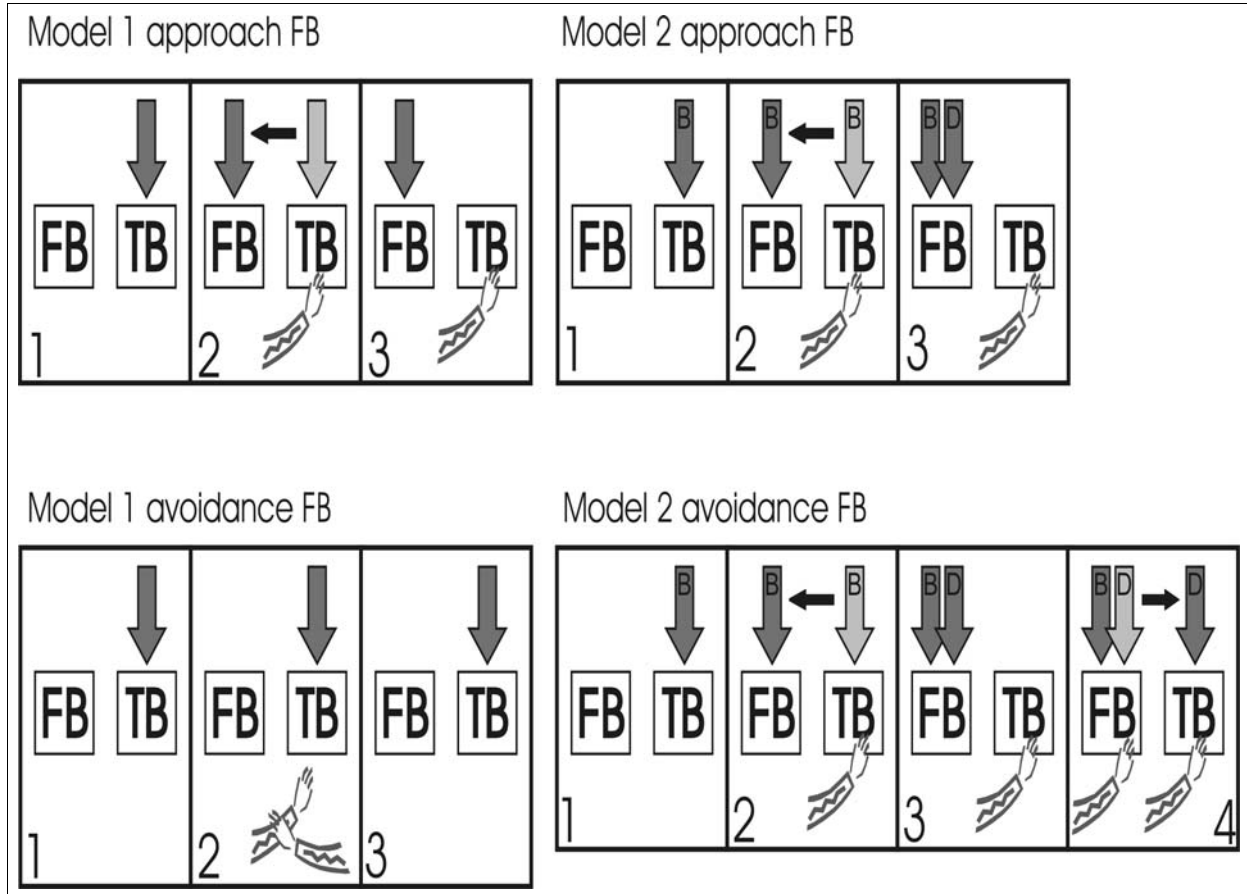


Figure 1. Two competing models of *selection by inhibition* in belief-desire reasoning. The top panels show how the models operate in the standard false belief task where the character has a desire to approach the target. For example, Sally might have a true-belief (TB) about the location of the marble (“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 an arrow. In both models, 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. Since for both models there are no further inhibitions in this task, the character’s predicted action can now be read off as approaching the FB location. The bottom panels 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 (frame 2). FB then attracts the desire index D (frame 3), which is subsequently inhibited for avoidance (frame 4), forcing the D index to shift back to the still inhibited TB.

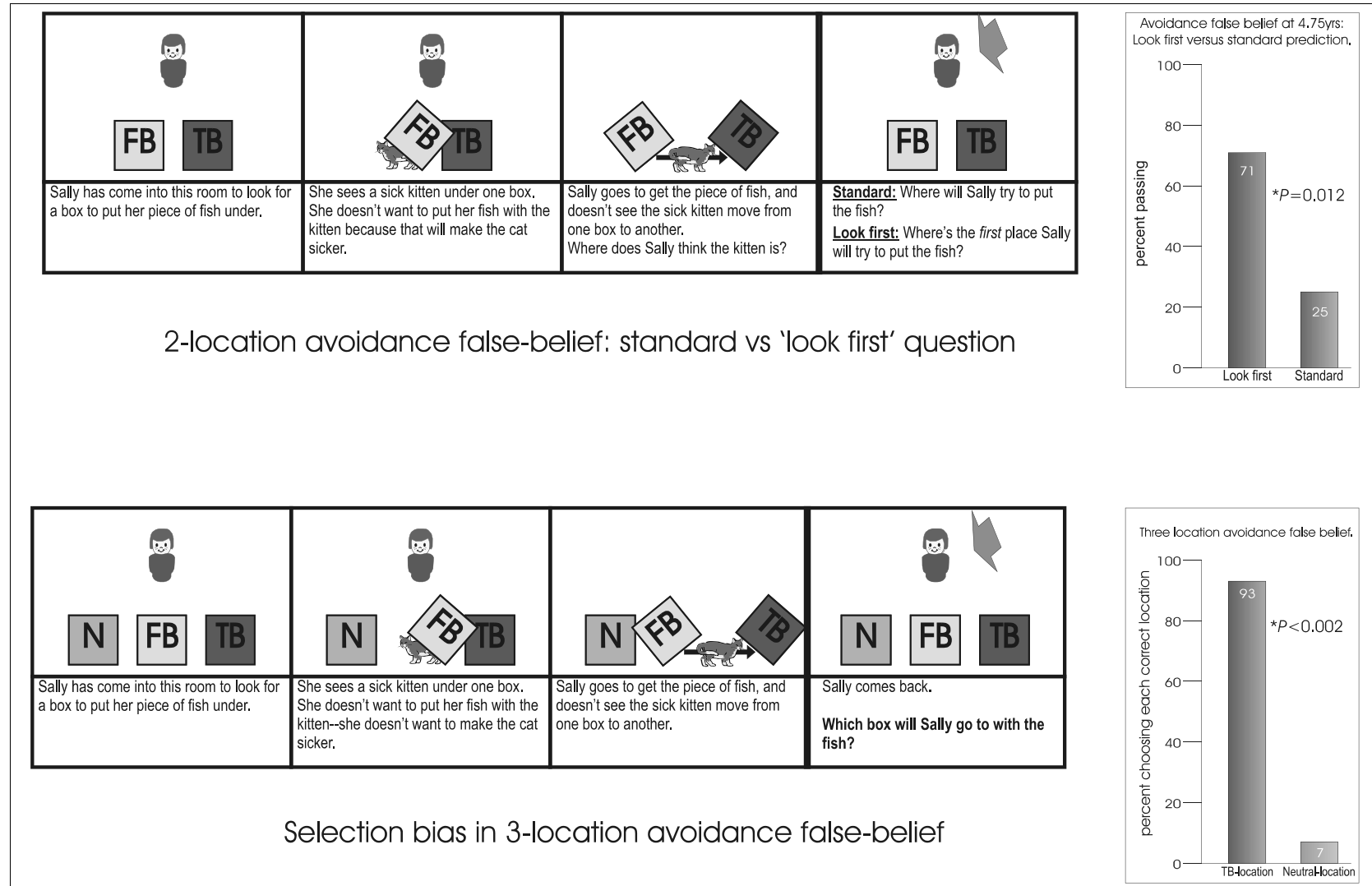


Figure 2. *Top panels.* An avoidance false-belief task with a standard prediction question is passed by only about a third of those four-year-olds who pass a standard approach false-belief task. If the question is modified slightly to a 'look first' format, most four-year-olds again pass.

Bottom panels. An avoidance false-belief task with 3-locations has two equally correct answers. Six-year-olds who pass a 2-location avoidance false-belief task show a strong bias to choose one of the correct answers in a 3-location task. They choose the true-belief (TB) location as predicted by the inhibition of inhibition model (Model 1).

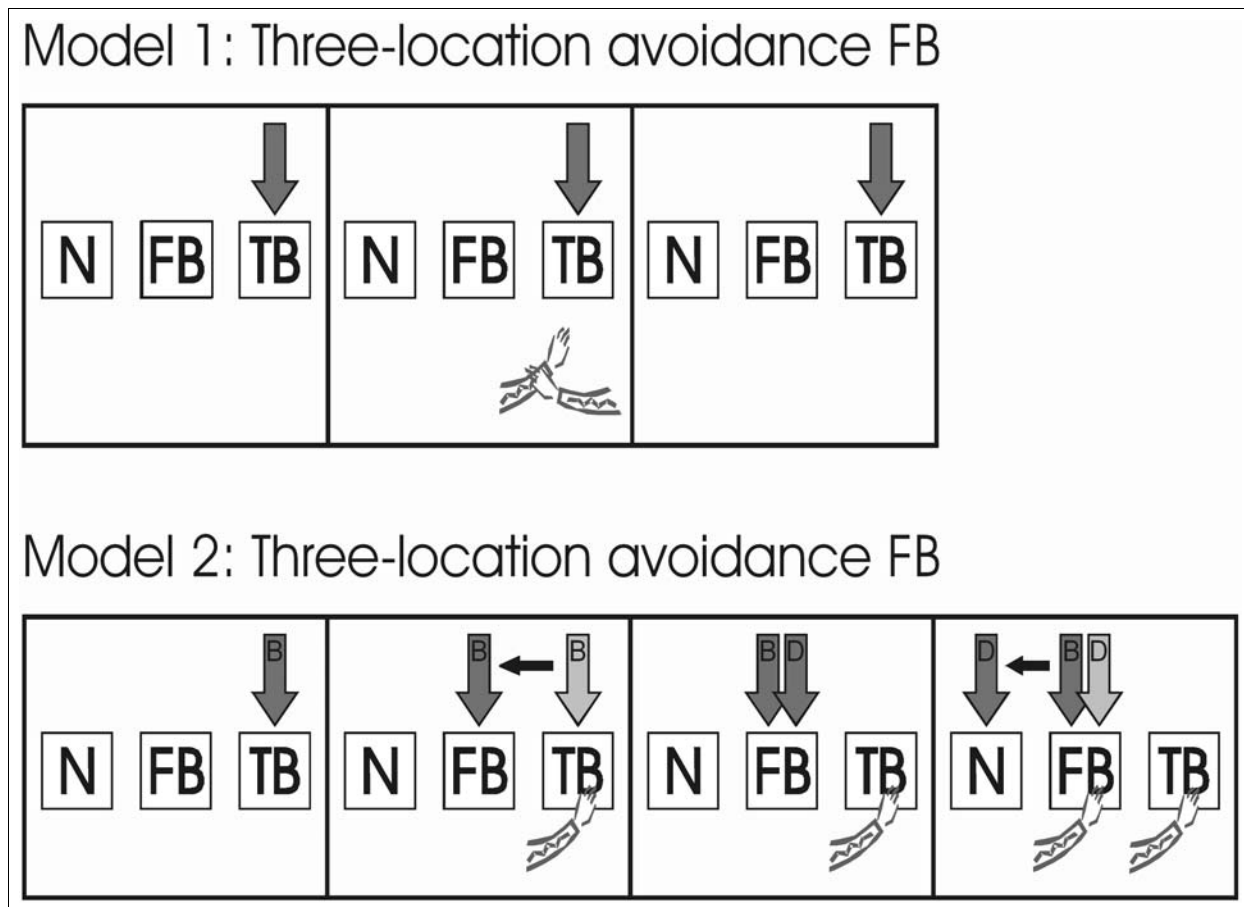


Figure 3. The two models make differential predictions for an avoidance false belief task with three-locations. With three locations, there are now two equally correct answers to where a character will go to avoid a given location. The character mistakenly believes that there is some object in the middle location (marked FB) which he or she wants to avoid. 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. Interestingly, the models disagree about which answer that will be. The top panel shows that for Model 1 the introduction of a third location makes no difference to how it operates. Because it 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 the character will go to the TB location and not the neutral location (N). The bottom panel shows that for Model 2 the introduction of the third N 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. Model 2 therefore predicts that subjects will be biased to predict that the character will go to the N location. In fact, as noted in Box 2, children show a strong Model 1 type bias. Model 2 is therefore ruled out.

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