Shared Representations of Belief and Their Effects on Action Selection: A Preliminary Computational Cognitive Model

Paul F. Bello (paul.bello@navy.mil)
Office of Naval Research, 875 N. Randolph St.
Arlington, VA 22203 USA

Abstract

New evidence from cognitive development suggests that action selection is contingent not only on one's own mental states (e.g. beliefs, etc.), but may also be affected by one's representation of the beliefs of others (Kovacs et al. 2010). Herein, I propose a preliminary computational model accounting for the general pattern of results in the recent study by Kovacs et al. that is broadly simulation-theoretic in nature, and briefly discuss its implications for computational cognitive architecture.

Keywords: Mindreading; Cognitive Architecture; Simulation Theory; Cognitive Development

Introduction

One of the key features of any complete computational theory of human cognitive architecture is a process-level explanation of how it represents and reasons about the contents of others' minds. This key question is driving a host of research projects in social neuroscience, developmental psychology, linguistics, philosophy of psychology and more recently in computational modeling of cognition. Many of the results to date in this area are due to a series of studies undertaken by cognitive developmental psychologists aimed at uncovering when in the developmental process children are able to reason about the false beliefs of others. Historically, these experiments have relied on tasks having verbal components that (in some cases) require the subject to understand what the word "think" or "believe" means. The results of this work indicate that children younger than roughly four years of age do not possess an adult "theory of mind" – or more clearly, a mature capacity to understand the beliefs of others.

Recently, a number of researchers have been using so-called non-verbal false belief tasks to perform the same sorts of experiments (Onishi & Baillargeon 2005). Strikingly, non-verbal false belief tasks seem to be passable by children as young as fifteen months, calling into question the original findings regarding a developmental transition at four years of age.

In a recent study published in *Science* magazine, Agnes Kovacs and colleagues suggest that along with adults, infants as young as seven months old have some appreciation of the beliefs of others (Kovacs et al. 2010). The results of their study seem to suggest that subjects automatically compute representations of others' beliefs and maintain them over time, even in the absence of the other. Further, these maintained representations of others' beliefs seem to affect reaction-times for the adult subjects on a simple button-pushing task and affect habituation times for infants in a similar way. All taken together, the paper concludes that maintaining representations of others' beliefs and having them be available to our practical reasoning system (e.g. planning, action-selection etc.) afford us faster socio-cognitive computations, and thus the ability to be more effective teammates or competitors. More specifically, the study also suggests that the representational format of our beliefs about the beliefs of others is the same as that of our own beliefs, and thus should be available to our action-selection systems. In this paper, I first explore Kovacs' results, and then try to account for them in the context of an extant cognitive-architectural account of belief ascription (Bello et al. 2007). Finally, I conclude with some speculative remarks regarding the counterintuitive nature of Kovacs conclusions, and what they might say about human performance on other kinds of cognitive tasks.

The Kovacs Experiments

The aim of the study by Kovacs and colleagues is to explore the possibility that our beliefs about the beliefs of other agents are represented in the same format as we represent beliefs about our environment. If this is the case, as the authors argue, our beliefs about the beliefs of others should affect our action-selection mechanisms, just as our beliefs about our environment clearly do. To test this hypothesis, Kovacs et al. designed a simple visual object detection task, and gave it to both adults (experiments 1-3) and seven-month old infants (experiments 4-7). The task involves the human participant P watching a scenario unfold along with another agent A. Each scenario consists of four stages. In the first stage, A enters the scene, and both A and P see a ball roll behind an occluder. In stage two, both A and P see the ball either stay behind the occluder, or roll out of view. In stage three, A leaves the scene and the ball either (i) stays behind the occluder, (ii) stays out of view, (iii) rolls from behind the occluder somewhere out of view, or (iv) rolls from out of view back to its place behind the occluder. In the fourth stage of the scenario, A returns to the scene and the occluder is removed. The adult participant's task is to press the space bar on a keyboard as soon as they detect the ball. Crucially, completion of this task has nothing whatever to do with the beliefs of A.

The four conditions in stage three correspond to four configurations of P's beliefs about A's beliefs. In the first condition, the ball moves and stays behind the occluder, even while A is gone from the scene, resulting in both P and

A having a true belief about the location of the ball. I adopt the Kovacs et al. notation, and refer to this situation as P+A+. In the second condition, the ball initially rolls behind the occluder, then rolls out of the scene with A still present. A leaves, and then returns, with the ball remaining out of view for both A and P, meaning that both A and P have true beliefs about the ball's location. I refer to this situation as P-A-. In the third condition, the ball initially rolls behind the occluder, A leaves the scene, and then the ball rolls from behind the occluder out of view, leaving A with a false belief about the ball's current location. I refer to this situation as P-A+. Finally, the fourth condition involves the ball initially moving behind the occluder, rolling out of the scene in A's presence, A then leaving the scene, and while A is gone, the ball returns to its' initial position behind the occluder, resulting in a false belief on A's part with regard to the ball's current location. This situation is labeled P+A-. The + symbol generally designates a belief that the ball is behind the occluder, and the – symbol generally designates a belief that the ball is somewhere out of the scene, so P+A+ or P-A- designates both agents having true beliefs about the ball's location behind the occluder or out of view (respectively), whereas mismatches such as P-A+ or P+A- indicate a false belief on the part of A.

Kovacs et al. hypothesized that reaction times involved with detecting the ball would be lower in situations where the ball was behind the occluder in a well-defined location, rather than when it had rolled out of the scene to parts unknown. Seven experimental conditions were run. For the sake of brevity, we will only concern ourselves with conditions one, two and three from a computational modeling perspective. The results of the first three experiments are as follows:

1. No significant differences were detected in reaction times when the participant had either (i) a belief that the object was behind the occluder, or (ii) a belief that A believed the object to be behind the occluder.
2. In stage four, rather than the agent returning, a pile of boxes returns to the scene. As in experiment one, no significant differences were detected.
3. In experiment three, the pile of boxes replaces A through all four stages. Reaction times were faster when the participant believed the ball to be behind the occluder, and slower in the other two conditions.

Experiments four through seven involved replicating the results of the three experiments above using seven month old infants, and a looking-time paradigm common to developmental studies. While these are interesting in their own right, they add little in terms of computational requirements over and above what would be needed to account for the results of experiments one, two and three. What the results of these experiments seem to show is that:

- The presence of an agent A (rather than boxes) induces participant P to automatically construct representations of the beliefs of the agent. This follows directly from the contrast between results from experiments one and three.
- Insofar as there seem to be no significant differences in reaction time when (i) P believes the ball to be behind the occluder and (ii) P believes that A believes the ball to be behind the occluder (even in false belief conditions where the ball has rolled away); the results suggest that both P's beliefs and A's beliefs are stored in the same representational format and are equally accessible to P's action-selection systems for use in the detection task. This follows from the results of experiment one.
- P's beliefs about A are maintained over time, even in A's absence, and have an effect on P's reaction time in the detection task. This follows from the manipulation in experiment two whereby a pile of boxes replaces A in stage four of the scenario, yet the reaction time results remain similar to those in experiment one.

I now turn to the task of providing a computational account of these general patterns of data, following prior work in constructing a cognitive-architectural account of belief ascription (Bello et al. 2007). As a disclaimer on what follows, I am not aiming to provide a quantitative data fit to Kovacs' results. To my knowledge, no computational model of belief ascription and tracking exists having millisecond-scale fidelity. I only seek to replicate the general functionality demonstrated by participants, and the effects of manipulations such as the replacement of A with a pile of boxes in experiment two and the total absence of A in experiment three.

Cognitive Architecture

The model of belief ascription used herein is developed within the Polyscheme computational cognitive architecture (Cassimatis 2002). Polyscheme was originally developed to give a competence-level account of infant physical reasoning, and has since been extended to applications in both natural language understanding and aspects of social cognition involving mental-state attribution

While some cognitive architectures including ACT-R, Leabra and 4CAPS make structural commitments about their components as being grounded in the literature on cognitive psychology and neuroscience; Polyscheme's structure is primarily inspired by the literature on "core knowledge" in child development along with the literature on embodied cognition. Polyscheme's basic set of services include components for reasoning about time, space, identity, categories, part-whole relations, causal relations, and hypothetical/counterfactual situations. These domain-general cognitive capabilities are Polyscheme's so-called *cognitive substrate*, and it is the coordination of these capabilities through Polyscheme's cognitive focus of attention that realizes complex cognition and resultant behavior. Polyscheme is designed such that each of the aforementioned components can be implemented using special-purpose data structures and algorithms. For example, temporal reasoning is implemented using constraint graphs, category hierarchies are implemented using the usual tree-like structures found in ontologies, and causal relations are captured using a probabilistic-relational formalism. The domain-general cognitive components are linked to one another through a relational interlingua that allows them to communicate with Polyscheme's cognitive focus of attention, which polls the components for their opinions on what is currently in focus, combines those opinions, and broadcasts the result back out to each component. Inference in Polyscheme takes the form of abduction which finds the most likely set of outputs given a set of inputs and sets of component-specific knowledge about the world. This process is discussed in greater detail elsewhere (Cassimatis et al. 2010).

Formal Preliminaries

Atoms in Polyscheme are the basic units of knowledge representation. Atoms are relational structures of the form $Rel([arg_1, .. arg_i], t, w)$, with *Rel* being the name of the relation, arg_x being relata, *t* being a temporal interval over which the relation holds (e.g. has a truth value), and *w* being the world in which the relation holds. In the presented models *w* will always have the default value R, though this won't be important for the purpose of our discussion. More importantly, atoms will have different values for *t* that determine when the atoms hold true/false, etc. Some atoms will have the value E substituted in for *t*, signifying that the relation holds over all temporal intervals and doesn't change through the course of computation. Other atoms will have specific timepoints such as t1, t2, etc. as a temporal interval. These atoms are called *fluents*, and their truth-values can change from timepoint to timepoint. As an example, the atom Color(sky, blue, E, R) represents the unchanging fact that the sky is blue, while Weather(outside, rainy, t3, R) states that at time t3, the weather outside is rainy. Many (but not all) of the atoms comprising the models I will present have an argument corresponding to the perspective in which the atom holds true. An example might be Location(ball, unknown, selfworld, t4, R). The third argument of the relation, called "selfworld" represents that from the model's perspective, the Location of the ball at time t4 is unknown. This argument isn't necessarily restricted to representing the model's perspective on the world; it can also represent the model's perspective of another agent's perspective on the world. For instance, Location(ball, garage, otherworld, t4, R) states that Polyscheme believes that from the perspective of another agent, the location of the ball is in the garage at time t4. We rely on this notational convention throughout the set of presented models to represent what Polyscheme believes the world to be like and what Polyscheme believes about the beliefs of other agent.

Belief Ascription

One of the central features of the Kovacs' tasks is that subjects seem to be automatically ascribing beliefs to other agents and maintaining them over a period of time, even in the agents' absence from the subjects' immediate view. In prior work, my collaborators and I have developed a broadly simulation-theoretic account of belief ascription within Polyscheme (Bello et al. 2007). In short, simulation-theoretic ascription of beliefs involves the ascriber constructing an internal simulation of the mental states of a target agent, and then using their own practical reasoning system within the context of the simulation to make predictions about what the target agent might do or think. The methods by which these simulations get populated vary across different simulation-theoretic accounts, and is, as of the present, an open research question. Our particular account of belief ascription relies on Polyscheme's ability to reason about categories, identity, constraints (both causal and non-causal), and counterfactual worlds. The models presented in this paper are constructed to explicitly represent counterfactual inferences in rule-based form in order to simplify presentation. The process of belief ascription begins when Polyscheme sees another agent. At this point, it creates a counterfactual world corresponding to the perspective of that agent, and also infers an identity relationship between itself and the agent that holds in its' own perspective. These atoms generally look like: IsA(other, Agent, E, R), IsCounterfactual(otherworld, selfworld, E, R) and SameAs(self, other, E, R). Polyscheme's representation of other agents' perspectives is counterfactual due to the fact that other agents may have beliefs about the world that differ from its' own. The rest of the ascription process is constituted by figuring out what to populate the other agent's perspective with, given what Polyscheme knows about the agent. The population process is called *inheritance* (figure 1), and corresponds to rules that govern how to populate Polyscheme's counterfactual simulation of the other agent's perspective. Once populated, atoms in the counterfactual simulation corresponding to Polyscheme's beliefs about the target agent's beliefs are reasoned about using all of Polyscheme's components, similar to the way Polyscheme reasons about the atoms comprising its' own perspective. Notice that inheritance rules such as those shown in figure 1 serve as filters through which self assumes the perspective of other. By themselves, these rules aren't pass-through filters that merely duplicate self's beliefs and assign them to the other agent. In figure 1, the inheritance rules detect when there are mismatches between events in the world as they are perceived by self and other. When such mismatches arise (as they do in Kovacs' false-belief conditions), the inheritance rules serve to suppress the inheritance of self's beliefs about events as they unfolded into "otherworld." Instead, "otherworld" gets populated with beliefs that capture the state of the world as "other" has perceived it to be. To borrow from the philosophical literature, inheritance rules are what implements the so-called *opacity* of mental states. Opacity is understood for our purposes to mean privacy and accounts for the basic intuition that different agents can have different beliefs about the same propositional content; in this case whether or not certain events in the world concerning ball motion have occurred. On this definition, being able to entertain the false belief of another agent requires the ability to maintain two *opaque contexts* (e.g. selfworld and otherworld).

Crucial to the results presented here, Polyscheme's action-selection mechanisms are simply rules, and therefore apply in both the selfworld and agentworld perspectives, allowing beliefs in agentworld to possibly have an effect on action-selection (figure 1). The motivation for this particular feature will be made clear in the general discussion. Differences in reaction time between when either self or other believe the ball to be behind the occluder versus when they believe the ball to be elsewhere are produced by having self posit the existence of a new unlabeled location when the ball is presumed to be elsewhere. The newly posited location invites Polyscheme to spend extra cycles trying to evaluate whether or not the ball might be at this unlabeled location rather than behind the occluder.

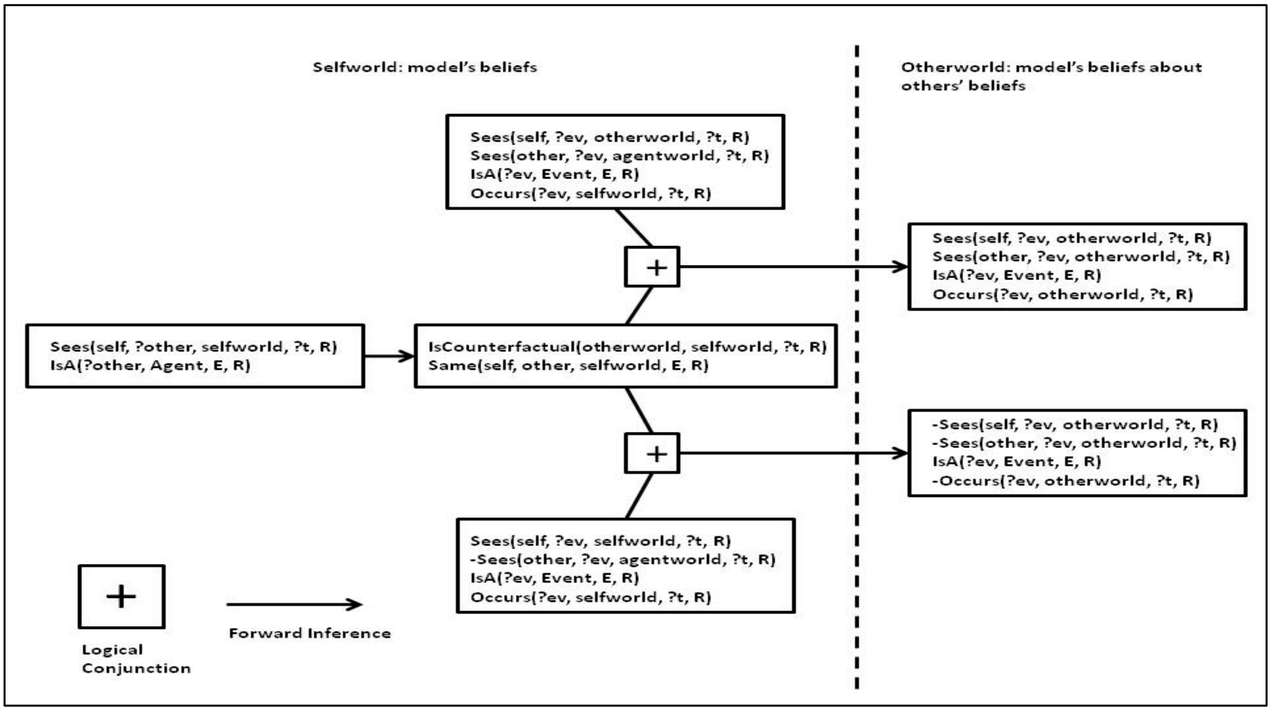

Figure 1: Inheritance of mutually perceived events from selfworld to otherworld

Model: Experiment 1

The task knowledge required for Kovacs' experiments is minimal, and is represented in figure 1. Briefly, there are a set of rules that govern events and their effects, a set of rules corresponding to action-selection, and a final set of rules defining the inheritance process. The rules governing events consist of a rule stating that if an object is at a particular location at some time t, then it likely will remain there; a rule stating that if an object rolls from behind an occluder out of view, then the object's new location is unknown and no longer behind the occluder; and finally that if an object rolls into view and behind an occluder, then its' new location is behind the occluder and is no longer unknown. Since both the agent and participant both know the object to initially be behind the occluder, I have simplified and not represented both of them seeing the object initially roll behind the occluder, as it contributes nothing to the task. We developed four sets of inputs corresponding to the four scenarios in Kovacs' experiments. In the P+A+, the input to the model consists of:

Sees(self, agent, selfworld, t1, R)
IsA(agent, Agent, E, R)
Location(ball, behindOcc, selfworld, t1, R)
Location(ball, behindOcc, otherworld, t1, R)

-Sees(self, BallRollsAway, selfworld, t1, R)
-Sees(other, BallRollsAway, selfworld, t1, R)
-Occurs(BallRollsAway, selfworld, t1, R)
-Sees(self, BallRollsBehindOccluder, selfworld, t3, R)
-Sees(other, BallRollsBehindOccluder, selfworld, t3, R)

-Occurs(BallRollsBehindOccluder, selfworld, t3, R)

Goal(self, detectBall, selfworld, t4, R)
-Satisfied(detectBall, selfworld, t4, R)
HalfLowered(occluder, selfworld, t4, R)
FullyLowered(occluder, selfworld, t5, R)

In this case, the ball remains behind the occluder for the duration. Neither self nor other see the ball roll away. The atoms Goal(self, detectBall, selfworld, t4, R) and -Satisfied(detectBall, selfworld, t4, R) state that at time t4, self has the goal of detecting the ball, and the goal is unsatisfied. The atoms describing the state of the occluder are self-explanatory and are meant to capture the fact that if Polyscheme knows at t4 where the ball is, it can press the space bar to detect the ball before the occluder is fully lowered. In the case where it doesn't know where the ball is, it waits for the occluder to be fully lowered before pressing the space bar. Similar configurations of inputs specify the P-A-, P-A+ and P+A- conditions. Given the P/A notation, Polyscheme takes the place of P, and the other agent whose beliefs are being reasoned about is A. The inheritance rules shown in figure 1 populate agentworld with event occurrences and non-occurrences conditioned on whether the event is mutually observed by P and A, or whether the event is solely observed by P.

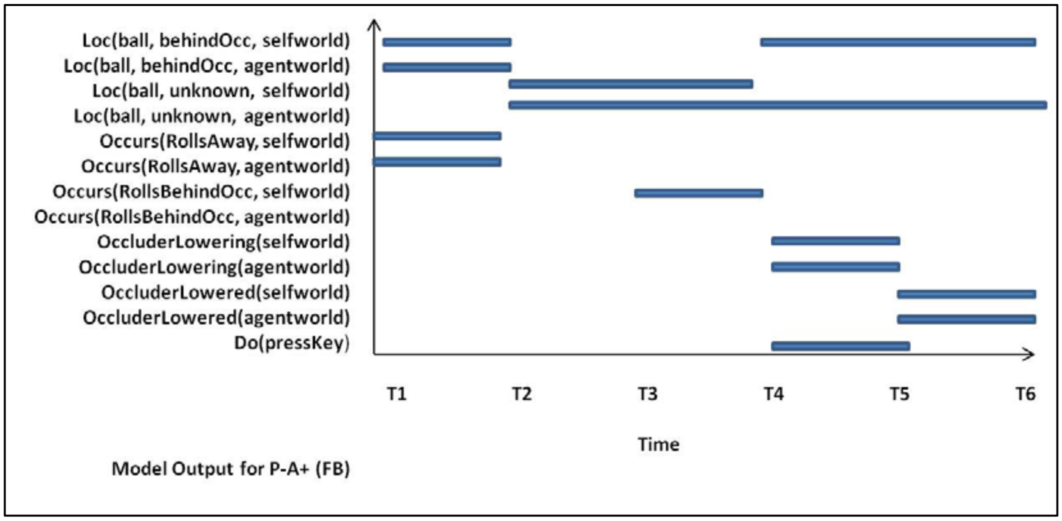

Figure 3: Model dynamics for P-A+ condition in Experiment 1

Experiment 1 Results

The results of the model runs across all four scenarios are captured in figure 3. As hoped for, the qualitative pattern of Kovacs' results are accounted for in terms of the number of computational cycles Polyscheme uses to make inferences in each condition. As a disclaimer, I assume no isomorphism between Polyscheme's computational cycles, and the reaction-time measure used in the Kovacs experiments, however, the computed correlation between the model results and a rough estimate of the reaction times reported in Kovacs' experiment 1 data is r = .939, p = .031.

As reported in Kovacs et al, the P-A- condition corresponding to both agents having no idea where the ball is consumes both the largest number of computational cycles in the model and generates the longest reaction time. In this condition, the model doesn't press the space bar until time t5, after the occluder is completely lowered. The P+A+, P-A+, and P+A- conditions produce both cycle times and reaction times that aren't significantly different from one another, since at least one of the agents believes (either truly or falsely) that the ball is behind the occluder at time t4, resulting in the space bar being pushed at time t4, before the occluder is completely lowered. In the P+A- condition, Polyscheme's action-selection rules have access to A's beliefs at time t4, and can use them to press the space bar, if warranted. The model execution trace for an example condition (P-A+) is given in figure 2, with blue lines representing when the corresponding fluent on the y-axis is true during model execution.

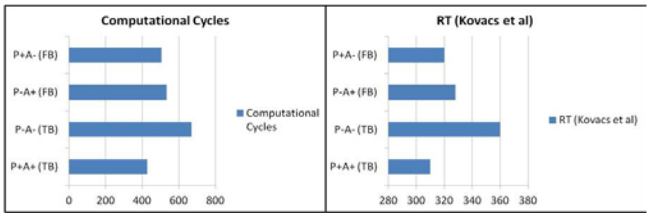

Figure 2: Model execution times vs. reported human Reaction Times for Experiment 1

Experiments 2 and 3 Results

Similar models were run in service of replicating results from Kovacs' experiments 2 and 3. Since the inheritance process is begun as soon as Polyscheme encounters another agent, and that it continually populates its' counterfactual simulation "otherworld" even in the absence of the agent, the results of Kovacs' experiment 2 are almost identical to the results of experiment 1. The only difference is that Polyscheme perceives an inert pile of boxes in the room at time t4 in place of the agent, but this has no effect on the ongoing counterfactual simulation. Cycle times for this condition are: P+A+ = 305, P-A- = 330, P-A+ = 300 and P+A- = 310. Correlation with rough estimates of Kovacs' experiment 2 data is reported as r = .689, p = .156. In experiment 3, the pile of boxes is present for the entire duration, and Polyscheme never encounters another agent. As expected, it doesn't construct a counterfactual simulation corresponding to another agent's perspective, and cycle times are predictably lower. In addition, the model data captures the general trend of longer reaction time when P doesn't know where the ball is in comparison to the conditions in which P knows the ball to be behind the occluder. Cycle times for this condition are: P+A+ = 343, P-A- = 419, P-A+ = 343 and P+A- = 419. Correlation with rough estimates of Kovacs' experiment 2 data is reported as r = .968, p = .016.

General Discussion

I have shown how a computational cognitive architecture equipped with no special representations for the beliefs of other agents can account for the data presented in (Kovacs et al. 2010) through the use of a general purpose set of inheritance mechanisms. While the inheritance process can be used to facilitate reasoning about the mental states of others, it is also the key component that enables reasoning about hypotheticals, future states of affairs, and counterfactuals. In the case of mental state attribution, inheritance is used in coordination with assertions about identity (e.g. self=other), categorization of others as agents, and general rules that govern action-selection to make predictions about what other agents might think and do. Rules that govern action selection take the following general form:

$$\mathit{Precondition1}(?x1, ?y1, ?world, ?t, R) \wedge \mathit{Precondition2}(?x2, ?y2, ?world, ?t, R) \wedge .. \wedge \mathit{Precondition\_N}(?xN, ?yN, ?world, ?t, R) \rightarrow \mathit{Do}(?actionname, ?t, R)$$

The italicized relation names correspond to appropriate atoms that represent Polyscheme's beliefs (e.g. Loc(ball, behindOcc, t1, R)) and/or desires (e.g. Goal(self, detectBall, selfworld, t4, R)), and the action that might follow from those (e.g. Do(pressKey, t4, R)). Notice that the ?world argument is a free variable, and can be bound by any available object that is a world. This allows Polyscheme's action-selection mechanism access to the beliefs of other agents, insofar as entertaining them helps to promote action-selection. The unsettling implication from Kovacs et al. suggests that the false beliefs of others might affect our action-selection. On the face of it, this is certainly not an adaptive feature, at least in some sorts of social interaction. But if we consider for a moment that when we perform a speech act corresponding to an assertion, the presumed effects of asserting include our interlocutor believing what we've asserted, and us having the belief that our interlocutor believes the assertion. The selection of future speech acts presumes the success of the transaction I just described. One way this might happen is through allowing our action-selection system access to these presumed beliefs of others. Since we usually don't make (intentionally) false assertions, such a mechanism seems like it would be very useful for pragmatic communication, at least when we aren't being intentionally deceptive.

The interesting and surprising results of the modeling work I've presented is that general purpose cognitive mechanisms which we assume present in infancy are sufficient to capture the general pattern of data uncovered by Kovacs and colleagues. Inferences about time, places, differences, identity, animate vs. inanimates, and hypothetical states of affairs are widely believed to be available to infants. When sequenced appropriately, this modeling effort shows them to be capable of enabling computations about the mental states of other agents. Further, and in general agreement with Kovacs, models such as the one developed in this paper ought to make us think twice about postulating innate cognitive modules to infants that are specialized for mental-state reasoning.

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