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Letter

Could It Be So? The Cognitive Science of Possibility

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As philosophers, linguists, and psychologists have long recognized, representing possibilities is central to mental life. Modal concepts (possible, necessary, impossible) are fundamental to moral reasoning (e.g., in distinctions between permissible, impermissible, and obligatory) and in formal mathematics and logic (e.g., where deductive necessity is the relation between axiomatic primitives and the conclusions licensed by derivational rules).

The concept of possibility, on its own, is fundamental to thought. From Bayesian perspectives, the human capacities for induction and decision making crucially depend upon representations of hypotheses (possibilities). Science is built on theories that make predictions about possible outcomes given particular circumstances, and on empirical attempts to falsify such predictions. Representations of possibility are central to sophisticated forms of thinking about time. Human mental time travel often involves consideration of mutually exclusive possible outcomes of uncertain future events, and of counterfactual (previously possible) outcomes of fixed past events. This capacity gives rise to adaptive behaviors like contingency planning and emotions like regret and relief.

Two companion articles by Leahy and Carey [1] and Redshaw and Suddendorf [2] focus in on one aspect of the psychology of representing possibility: the ontogenetic and phylogenetic origins of the ability to think about mutually exclusive possibilities. The articles arose from different backgrounds.

In the background of Leahy and Carey's article [1] is the age-old question of the ontogenetic origins of abstract, combinatorial thought. Are philosophers such as Descartes [3] and Davidson [4] correct that such thought arises, both in ontogeny and phylogeny, with the emergence of natural language? Or are philosophers such as Fodor [5] right that such thought predates language? These questions lead to a focus on the capacity to represent two incompatible possibilities concerning an actual state of affairs as a case study. Leahy and Carey argue that this ability requires marking representations as merely possible in a manner that endows them with a logical structure.

In the background of Redshaw and Suddendorf's article [2] is the question of mental time travel and its role in human development and evolution. The article particularly focuses on the ability to imagine alternative timelines, or multiple timelines of which only one can be true of the actual world. This focus represents a break from long-standing debates in the mental time travel literature, which have primarily been concerned with children's and animals' ability to imagine and link events from a single timeline. Redshaw and Suddendorf's central proposal is that the capacity to envision alternative timelines emerging from 'temporal junctures' can explain children's acquisition of contingency planning, counterfactual thinking, and more.

In spite of these different foci, our two pieces converge in deep ways. Both approaches take as a starting point evidence that young children and animals fail tasks that require simultaneously considering mutually exclusive possibilities [6,7]. Both articles are concerned with changes in how possibilities are represented across the human life span and with differences across species. And both argue for a fundamental developmental change around age 4 years. Furthermore, both also review conflicting evidence that animals and infants succeed on tasks that would likewise seem to require representing and comparing alternative possibilities. To resolve these apparent conflicts, Leahy and Carey distinguish minimal representations of possibility from modal representations of possibility, or representations of possibility as such (a distinction endorsed by Redshaw and Suddendorf). Redshaw and Suddendorf distinguish between being in a state of uncertainty and having a metarepresentational awareness of uncertainty (a distinction endorsed by Leahy and Carey).

Nonetheless, differences remain. Leahy and Carey are exclusively concerned with the developmental changes that occur in the early preschool years, whereas Redshaw and Suddendorf characterize a developmental sequence into the school years, explaining it in terms of increasingly complex representations of temporal junctures.

Although we agree that there is likely to be an important developmental change in the capacity to represent possibilities that occurs around 4 years of age, we differ in our proposals for how to constrain an account of the mechanisms that underlie that change. Redshaw and Suddendorf suggest that representing possibility originates from the fundamental capacity to metarepresent

[8]. Only by representing that a representation of a past or future event may not necessarily correspond to the actual event (i.e., reflecting on the representational relation) may humans come to conceptualize possibility as such. Leahy and Carey suggest that language learning may provide a workspace for bootstrapping that scaffolds the construction of modal concepts.

Our two companion pieces complement each other in pointing out the deep commonalities in the findings across the two research traditions, and raise further questions concerning the relations between mental time travel and modal reasoning in general. Both set the stage for detailed proposals about what exactly is changing over childhood, and what mechanisms underlie these changes. Both equally set the stage for detailed proposals of what has changed over evolution; what new representational/computational devices came into being, and what selection pressures played a role in their emergence.

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Spotlight

Human Decision-Making beyond the Rational Decision Theory

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Two recent studies (Farashahi *et al.* and Rouault *et al.*) provide compelling evidence refuting the Subjective Expected Utility (SEU) hypothesis as a ground model describing human decision-making. Together, these studies pave the way towards a new model that subsumes the notion of decision-making and adaptive behavior into a single account.

The Rational Decision Theory makes the core prediction that choices should maximize the SEU based on multiplying the subjective probability and value of choice outcomes [1,2]. While in some specific, more- or less-complex circumstances, human choices admittedly violate this prediction, the SEU hypothesis has long been viewed as a ground model describing human decision-making. However, two studies published in 2019 [3,4] provide the first compelling evidence refuting this idea and pave the way towards a new ground model of human decision-making.

Both studies investigated human and non-human primate decision-making in a simple decision situation: namely choosing between two lotteries, each proposing a reward that will be potentially delivered after the choice. As in real life, participants experienced and learned reward probabilities associated with each lottery along a series of successive choices (Figure 1). Through extensive and rigorous computational modeling and model fitting analyses, both studies show that the choices of participants derived from the additive or independent contribution of (subjective) reward probabilities and values rather than from computing SEUs. Reward probabilities contributed more than reward values, indicating that humans prefer safer choices in agreement with the well-known risk-aversion effect [5]. Using neuroimaging, Rouault *et al.* further revealed that choice computations involved the dorsomedial prefrontal cortex, which activations indeed varied with these quantities independently [3]. Farashahi *et al.* showed that this independent contribution also held in monkeys (who unlike humans, exhibited risk-seeking behavior), with further supporting evidence from neuronal recordings in the dorsolateral prefrontal cortex [4]. The independent contribution is notably observed in a situation where SEUs are especially easy to compute, suggesting that the result generalizes to more complex situations, at least when reward probabilities are not explicitly provided to participants.

Farashahi *et al.* investigated the latter case by verbally instructing participants that one lottery's attribute (e.g., its size) actually signaled its probability to deliver rewards [4]. Interestingly, they reported the opposite result: participants' choices reflected SEU computations rather than independent contributions. Farashahi *et al.* also trained monkeys to perform the same task but through extensive reinforcement learning. They observed monkeys' choices to reflect both SEU