

Evolved cognitive biases and the epistemic status of scientific beliefs

Helen De Cruz · Johan De Smedt

Published online: 28 November 2010
© Springer Science+Business Media B.V. 2010

Abstract Our ability for scientific reasoning is a byproduct of cognitive faculties that evolved in response to problems related to survival and reproduction. Does this observation increase the epistemic standing of science, or should we treat scientific knowledge with suspicion? The conclusions one draws from applying evolutionary theory to scientific beliefs depend to an important extent on the validity of evolutionary arguments (EAs) or evolutionary debunking arguments (EDAs). In this paper we show through an analytical model that cultural transmission of scientific knowledge can lead toward representations that are more truth-approximating or more efficient at solving science-related problems under a broad range of circumstances, even under conditions where human cognitive faculties would be further off the mark than they actually are.

keywords Evolutionary arguments · Evolutionary debunking arguments · Intuitive ontologies · Scientific knowledge · Biased cultural transmission

1 Introduction

What is the relationship between the evolved structure of the human brain and scientific knowledge? A growing body of empirical evidence from developmental

Electronic supplementary material The online version of this article (doi:[10.1007/s11098-010-9661-6](https://doi.org/10.1007/s11098-010-9661-6)) contains supplementary material, which is available to authorized users.

H. De Cruz (✉)
Centre for Logic and Analytic Philosophy, Katholieke Universiteit Leuven,
Kardinaal Mercierplein 2, 3000 Leuven, Belgium
e-mail: helen.deacruz@hiw.kuleuven.be

J. De Smedt
Department of Philosophy and Ethics, Ghent University, Blandijnberg 2, 9000 Ghent, Belgium
e-mail: johan.desmedt@ugent.be

psychology, neuroscience and cognitive psychology indicates that the way humans perceive and conceptualize the world is shaped by evolved cognitive inference mechanisms. These findings can be incorporated in naturalistic theories of mental content that propose that the proper function of our cognitive processes is to promote survival and reproduction (e.g., Millikan 1984; Rowlands 1997). The implications of this evolutionary picture for the epistemic status of scientific and other forms of beliefs remains a matter of debate. Does the fact that our cognitive apparatus has an evolutionary origin provide us with a justification for scientifically informed beliefs, or are we to treat them with suspicion? To address these questions, we look at two types of arguments that connect evolution and beliefs: *evolutionary arguments* (EAs) and *evolutionary debunking arguments* (EDAs). Both types of argument agree that evolutionary considerations have implications for the epistemic standing of beliefs. Both are also committed to evolutionary psychology in the broad sense, i.e., they hold that evolutionary pressures, in particular natural selection, are important forces in shaping cognition.¹ They reach contradictory conclusions about the implications of evolutionary psychology for the epistemic justification of beliefs. EAs state that evolution will tend to select for belief-formation mechanisms that are reliable, whereas EDAs imply that evolution is not a truth-tracking, but a fitness-enhancing process.

This paper examines the implications of the evolutionary origins of our cognitive faculties for the epistemic standing of science. First, we briefly outline the role of cognitive biases in human cognition (Sect. 2). We argue that these biases also play a role in scientific practice (Sect. 3). Next, we discuss evolutionary arguments and evolutionary debunking arguments in relationship to scientific practice (Sects. 4 and 5). We show that for any belief that can be plausibly thought to be influenced by evolved cognitive predispositions it is possible to construct both an EA and an EDA. This indicates that evolutionary biological considerations may not be decisive for the epistemic justification of scientific beliefs. We therefore shift our focus to the cultural dynamics of scientific practice, by presenting an analytical model (Sects. 6 and 7) that suggests that cultural transmission of scientific knowledge can lead toward representations that are more truth-approximating under a broad range of circumstances, even if human cognitive faculties were further off the mark than they actually are.

Before proceeding, we make explicit two basic assumptions that underlie this paper. First, evolutionary considerations are only relevant for the justification of beliefs from an externalist perspective. For externalists who favor a causal account, beliefs are only justified if there is a proper causal relationship between a belief and the external world. As we shall see, both EAs and EDAs rely on an externalist, causal account of knowledge acquisition. Second, we assume a form of basic or ontological realism; in other words, we will assume that there is an external and observer-independent reality.

¹ This broad position is not to be confused with evolutionary psychology in the narrow sense as developed by the so-called “Santa Barbara school”, in particular by John Tooby and Leda Cosmides.

2 Cognitive biases and the perception of reality

Is there a limit to what humans can know? Some authors (e.g., Dennett 1991) are convinced that our cognitive faculties are in principle able to tackle all aspects of nature, whereas others (e.g., Sullivan 2009) argue that some parts of reality will always remain outside the reach of our cognitive faculties. This skepticism is often motivated by an appeal to the evolved nature of the human brain. Plantinga (1993, p. 218), for example, argues that ‘if our cognitive faculties have originated as Dawkins thinks [i.e., through natural selection], then their ultimate purpose or function [...] will be something like *survival* (of individual, species, gene or genotype); but then it seems initially doubtful that among their functions—ultimate, proximate or otherwise—would be the production of true beliefs.’ Several philosophers of mind (e.g., Millikan 1984; Rowlands 1997; Akins 1996) propose that mental content can be understood as a product of natural selection: the proper function of some mechanism, trait, or process in evolved organisms is ultimately relative to fitness, and the brain has as proper function the production of beliefs that are fitness-enhancing.

Faced with a rich environment, and with limitations in time and cognitive resources, animal brains need to be highly selective about the information they process. Information that has potentially large consequences for an animal’s fitness needs to be prioritized, whereas cues that are irrelevant for fitness are often ignored. For example, animal visual systems typically pick up only a small part of the electromagnetic spectrum. In contrast to humans and other mammals, pollinating insects can see ultraviolet light. In the co-evolution of flowers and pollinators, many flowers have developed ultraviolet cues that help insects find nectar, such as concentrations of ultraviolet streaks that guide bees into the centre of a flower, thereby promoting pollination (Miller et al. 2011). The human visual system ignores ultraviolet light because it did not play a role in our evolutionary history (e.g., in terms of food or sexual selection). There is little reason to assume that the limited part of reality we perceive represents an objective translation of that reality—animals, including humans, produce simplified approximations of reality that tend to be adaptively useful within their ordinary world. Sullivan (2009) considers deerflies: they conceptualize sources of food like deer, cattle or humans of which they suck the blood as middle-sized objects that are in motion. A deerfly has no cognitive resources that enable it to differentiate between a truck and a large mammal. Human cognitive faculties, too, are not aimed at the disinterested representation of facts, but at representations that are relevant for the organism’s fitness. Our sensation of temperature, for instance, is closely related to the skin’s starting temperature; rather than detachedly reporting a change in temperature, an already hot skin will register a warm impulse as hotter and more discomforting than a cooler skin (Akins 1996).

The impact of evolutionary pressures on human mental content can be weak or strong, depending on the model one develops. A weak version (e.g., Rowlands 1997) restricts the impact to fairly basic representational mechanisms, mainly perception, such as the spectral-frequency band in which the human ear can receive acoustic signals. A stronger version would extend the impact to our conceptual knowledge as well. One reason to adopt this latter version is that it is difficult to

make a clear distinction between purely perceptual and conceptual mental content. Higher-order cognitive capacities are almost always involved in simple cases of perception. Even the belief that one has hands is informed by higher-order processes, such as an internally generated body schema. When damaged, this leads to finger agnosia, the inability to recognize one's own hands or fingers in spite of intact visual and tactile perceptual input (Osawa and Maeshima 2009). Moreover, a burgeoning field of experimental evidence from developmental psychology and cognitive neuroscience indicates that the human mind imposes a variety of conceptual structures onto the sensations it receives. Human cognition is characterized by a host of higher-level specialized inference mechanisms, which we term intuitive ontologies, following Boyer (2000). In order to interpret the world around us, we make inductive inferences about objects, and categorize them into a relatively small set of classes that are meaningful from an evolutionary point of view, such as 'artifact', 'animal' and 'person'. Categorization is vital for survival and reproduction, because it enables animals to make fast decisions based on limited sensory information—it is therefore unsurprising that even organisms with very small brains, such as insects, perceive the world in terms of high-level concepts and categories (Chittka and Niven 2009).

Intuitive ontologies guide inductive inferences about specific categories of objects in the world, such as persons (intuitive psychology), inanimate objects (folk physics), animals and plants (intuitive biology). We draw on intuitive psychology (also termed theory of mind) to predict and understand the behavior of people and other agents. This allows us to attribute internal mental states to others in order to explain their behavior. The recognition that mental states can differ from the state of the external world (i.e., understanding false beliefs) develops cross-culturally in children between the ages of four and five (Callaghan et al. 2005). Reasoning about mental states robustly activates a distributed network of neural circuits, including the medial prefrontal cortex, superior temporal sulcus, and temporal poles. The same network is activated across a wide diversity of mentalizing tasks, such as hearing stories, interpreting cartoons, or even watching simple geometric shapes 'chasing' each other (Gallagher and Frith 2003).

Humans rely on folk physics to predict and understand the behavior of inanimate objects. It is based on principles like contact (objects need to be in direct contact to set each other in motion), cohesion (bounded objects normally do not fall apart) and continuity (an object continues to exist when out of sight). Looking time experiments (e.g., Spelke et al. 1995) indicate that infants as young as 4 months reason about inanimate objects in this way. They are surprised when a solid-looking object suddenly falls into pieces without any apparent external cause, or when an inanimate object apparently causes the motion of another one without direct contact (no action at a distance). As can be expected, the brain areas subserving the perception of mechanical movement (such as the medial temporal gyrus) are distinct from those that detect social agency (Beauchamp et al. 2002).

Another intuitive ontology concerns living things (animals and plants). Young children spontaneously attribute a hidden essence to explain the development and behavior of organisms (Gelman 2004). This psychological essentialism leads 4-year-olds to predict that an apple seed, planted in an orchard with pear trees will still grow

into an apple tree, and that a young kangaroo raised by goat foster parents, will hop rather than climb even if it never saw another kangaroo in its life (Gelman and Wellman 1991). Essentialism about living things has been cross-culturally observed in children, who are often more essentialist than adults: 5-year-olds believe that French babies brought up by English-speaking parents will grow up to speak French; Indian children think that a Brahmin child will remain Brahmin, even when raised by untouchables (Gelman 2004). Conceptual knowledge of animals and plants is stored in specialized areas of the brain, such as the lateral occipital cortex. Remarkably, damage to this area results in a permanent disability to reason about living things. Farah and Rabinowitz (2003) studied a boy who suffered a lesion in his occipital cortex shortly after birth. Even 16 years later, he is unable to recognize animals and plants or answer questions about them, although his knowledge about artifacts is comparable to that of normal subjects. These and similar empirical studies suggest that intuitive ontologies develop early and reliably without instruction, that they are stable across cultures, and are associated with dedicated neural structures.

3 Cognitive biases and scientific practice

From an evolutionary perspective, science is a recent development in our species. Thus, scientists have to draw on the same cognitive resources as other people, and they are subject to the same cognitive limitations. If humans conceptualize and reason about the world in terms of a limited number of intuitive ontologies, one could expect that intuitive ontologies play a role in scientific understanding. In an earlier paper (De Cruz and De Smedt 2007), we argued that this is the case in archeology and paleoanthropology. Like other species, humans have specialized inference-systems to reason about their conspecifics. For humans, this detection is neurally subserved by amongst others specialized face-recognition, body part recognition, and theory of mind. Bonatti et al. (2002) showed that this recognition of conspecifics arises early in infancy: though 10-month-olds fail to discriminate between dissimilar looking artifacts, they can distinguish humans from other animals, indicating that they make a fundamental human-nonhuman distinction. Cross-culturally, humans are not categorized as ‘animals’, and most people (except those with western schooling) will deny that humans are animals (Waxman 2005). This intuitive ontology has played a role in modern science, most notably in the domains of archeology and paleoanthropology: the intuition that humans are special gave rise to the working hypothesis that human evolution must be distinct from other forms of organic evolution. Until the mid 1970s, the overwhelming majority of scientists working in this field were convinced that human evolution was linear, and that only one hominid species existed at any one time. This linear model stood in sharp contrast to evolutionary models of all other organisms which were bush-like, with many branches and dead ends. As Foley (2001) pointed out, these models of human evolution were not motivated by evolutionary theory, which firmly rejects a radical distinction between humans and the rest of the organic world, but by the tacit assumption that humans are unique. This single species model was only abandoned when Leakey and Walker (1976) reported their discovery of skulls of the gracile *Homo ergaster* and the robust *Paranthropus boisei* in the same

archaeological layer, unequivocally showing that human evolution was bushy after all. Further archeological finds confirmed that several hominid species co-existed during most of human evolution.

Another example of the role of intuitive ontologies in scientific understanding is essentialism in biology. Hull (1964) observed that essentialism in taxonomy (and biology in general) resulted in 2000 years of stasis: before Darwin and other evolutionary theorists, biologists like Linnaeus did not make any significant theoretical contribution to taxonomic theory since Aristotle laid its foundations in the fourth century BC. The view of a species essence as underlying causal mechanism for development and behavior has dominated most pre-Darwinian biological thought until well into the eighteenth century (Stamos 2005). In questionnaire-based studies (e.g., Samarapungavan and Wiers 1997), a large percentage of children spontaneously voice essentialist ideas about the origin of species. Their ideas show remarkable similarities to historical theories, including Greek essentialism or accounts of small, micro-evolutionary changes within species' boundaries, as fleshed out by the eighteenth century French natural historian Buffon. Perhaps the intuitive appeal of essentialism can partly explain the slow acceptance of evolutionary theory. It took this theory almost a century to take root among professional biologists; even today it is not widely accepted among non-scientists. Shtulman and Schulz (2008) indeed found that adults who hold on to an essentialist conception of species understand the mechanism of evolution through natural selection less well than those who hold less essentialist views.

The influence of cognitive biases not only applies to the content of our scientific beliefs, but also to our metatheoretical assumptions. Take, for example, the intuition that all contingent states of affairs have a cause for their existence. Scientists rely on this principle, though they cannot demonstrate its reliability. The propensity to infer causes probably has a long evolutionary history, as it has been demonstrated in apes as well (Bräuer et al. 2006). The search for (non-obvious) causes of events arises in very young children, leading some psychologists (e.g., Brewer et al. 2000) to liken children to scientists, engaged in theory formation and hypothesis testing. Others have reversed this analogy, arguing that in fact scientists are like children: Gopnik and Meltzoff (1997), for instance, see science as a byproduct of our universal search for causal explanations, emerging in early childhood. Looking time experiments (Saxe et al. 2005) indicate that this search for causes is already present in 12-month-olds, who expect a human hand, rather than a toy animal, to be the cause of an object falling on a stage. Preschoolers readily infer unobservable causes in diverse domains: they invoke unobservable mental states to explain the behavior of agents (Callaghan et al. 2005), unobservable physical forces to account for the motions of inanimate objects (Shultz 1982), and invisible essences to predict and account for the growth of biological organisms (Gelman and Wellman 1991). This intuition of causality illustrates the continuity between everyday and scientific reasoning.

4 Evolutionary arguments

The evolutionary argument (EA) contends that natural selection will form animal brains that tend to produce true beliefs, because true beliefs are essential for

adaptive decision making. Cognitive faculties that are widely off the mark would seriously compromise a creature's ability to survive and reproduce. As Quine (1969, p. 126) put it 'Creatures inveterately wrong in their inductions have a pathetic but praiseworthy tendency to die before reproducing their kind.' This position goes back at least to the eighteenth-century common sense philosopher Thomas Reid, who considered the consequences of rejecting those beliefs that our cognitive faculties naturally produce: 'I resolve not to believe my senses. I break my nose against a post that comes in my way; I step into a dirty kennel; and after twenty such wise and rational actions, I am taken up and clapt into a mad-house [...] I gave implicit belief to the informations of Nature by my senses [...] I find, that without it I must have perished by a thousand accidents [...] I consider this instinctive belief as one of the best gifts of Nature' (Reid 1764, pp. 413–415). A detailed defense of EAs comes from Boulter (2007), who argues for an updated form of common sense philosophy. Common sense beliefs are non-inferential, basic beliefs that do not have to be justified by reasoning or by reference to other beliefs, like our belief in the past, in the existence of other minds, or our reliance on memory. As we have seen in Sect. 2, intuitive ontologies furnish us with a wide variety of common sense beliefs, such as the belief that an unsupported object will fall downward (intuitive physics), that other agents act on the basis of their internal mental states (intuitive psychology), and that tadpoles grow into frogs even though they do not look alike (intuitive biology). To Boulter (2007), these basic beliefs derive their epistemic justification from their adaptive value. His EA can be summarized as follows:

1. Animals that can successfully interact with the world have a higher chance of passing on their genes than animals that do not successfully interact with the world.
2. Beliefs about the world that accurately track those states of affairs in the world are, on the whole, better guides to action than are false beliefs.
3. Therefore, natural selection will favor those animals with reliable sensory and belief formation systems insofar as those sensory systems and beliefs have a bearing on the animals' fitness.
4. Common sense beliefs have direct bearing on human fitness.
5. Therefore, human common sense beliefs will tend to be correct.

Similar EAs can be found in Fodor (1981) and Stewart-Williams (2005). In this paper, we will neither evaluate nor defend the merits of the EA for common sense beliefs, but only consider whether this argument can be used to justify scientific beliefs. As can be seen in premise 3, the EA has the important qualification that the beliefs will only be reliable to the extent that they have a bearing on an organism's fitness. Defenders of EAs argue that they only hold under conditions that resemble the ones in which our cognitive faculties evolved. Stewart-Williams (2005), for example, argues that causal cognition only yields reliable intuitions in our everyday understanding of the world, but that it may be unreliable in circumstances outside this narrow range, such as when it produces philosophical or scientific beliefs—for instance, we cannot rely on causal intuitions to explain events at the quantum level where the common sense belief that every event must have a cause has proven unreliable. Most scientific knowledge falls outside of ecologically relevant

conditions. Intuitive ontologies may be effective for everyday understanding, but they can go awry in such domains as probability theory, cognitive neuroscience or evolutionary theory. Scientific practice itself cannot have exerted any selective influence on our cognitive systems. The fact that scientific practice as we know it is only a few hundred years old makes it very unlikely that such selective pressures, if any, would have perceptible effects. If the reproductive success of fundamentalists who reject evolutionary theory in favor of creationism is any guide, holding wrong scientific beliefs does not seem to have any negative effects on one's fitness.

5 Evolutionary debunking arguments

Does natural selection promote the formation of true beliefs? Evolutionary theorists and philosophers have offered at least four types of situations where it does not. First, many false beliefs, including systematic fallacies, do not compromise fitness, and thus cannot be honed by natural selection. As Pinker (2005, p. 18) puts it: 'Members of our species commonly believe, among other things, that objects are naturally at rest unless pushed, that a severed tetherball will fly off in a spiral trajectory, that a bright young activist is more likely to be a feminist bankteller than a bankteller, that they themselves are above average in every desirable trait [...] The idea that our minds are designed for truth does not sit well with such facts.' More generally, we can expect that beliefs that have no bearing on an animal's fitness are not subject to natural selection. Second, natural selection can favor cognitive faculties that are more often incorrect than correct under specific circumstances. This scenario is explored by the 'better safe than sorry argument' (a term coined by Stephens 2001), which states that cognitive processes may sometimes err on the side of safety. If the costs or payoffs of false positives and false negatives are asymmetric, natural selection will tend to promote beliefs that yield the highest payoffs or incur the least costs. Take agency detection: it is less costly to discern an agent when none is present (a false positive) than it is to fail to detect an agent that is present (a false negative)—the first results in a small waste of time and energy, whereas the second may lead one to miss out on a meal or to become one. For the same reason, creatures are expected to be excessively cautious when deciding whether a potential mate is member of the same or of a different species. In this case, the cost of a false positive (mistaking a member of another species for a member of one's own) can be disproportionately high for females, as it might result in investing time and resources in inviable or sterile offspring (Godfrey-Smith 1991). Third, cognitive processes can deviate from the truth due to a fitness trade-off between accuracy and efficiency: given that animals have limited time and resources, they will sometimes be better off with fast heuristics that may occasionally or even often misfire. There is little point in carefully and elaborately choosing the best escape route when faced with a predator. As the world is too complex to be understood in its entirety by organisms limited in space, time and cognitive resources, animals must resort to heuristics to make the world more tractable. This usually enables them to act adaptively under uncertainty, but it sometimes leads to characteristic biases. Such heuristics and biases have been

experimentally observed in humans as well as nonhuman animals (see e.g., Real 1991, for characteristic biases in foraging bumble bees). Fourthly, and more tentatively, some misbeliefs might confer an adaptive advantage because of their misalignment with reality. McKay and Dennett (2010) cite the ‘above average’ effect as a case in which it is adaptive to be wrong. This is a well-established tendency in neurologically normal people to overestimate their own positive qualities, to underestimate their negative qualities compared to others, and to value their own children as smarter, kinder and more beautiful. From an evolutionary perspective, one can easily see how this bias can be adaptive, as it leads to increased fitness by compelling one to pay more attention to one’s own needs and the needs of one’s offspring.

Given that natural selection does not reliably preserve or promote true beliefs, the evolutionary origins of our cognitive faculties can cast doubt on their epistemic justification. Kahane (in press) offers a general schema for such evolutionary debunking arguments (EDAs):

1. We believe that p , because we have an intuition that p , and there is an evolutionary explanation of our intuition that p .
2. Evolution is not a truth-tracking process.
3. Therefore, we are not justified in believing that p .

To take a simple example: Thelma believes her children are more beautiful and smarter than average, and there is a good evolutionary explanation for this belief. Her belief is not properly causally connected to facts in the world, namely the objective qualities of her children. Therefore, Thelma’s belief is unjustified.

Is science vulnerable to EDAs? As Kahane (in press) has observed, once one allows EDAs, it is difficult to see where they would not apply. In the case of moral beliefs, for instance, EDAs call into question not just a subset of moral judgments (e.g., prioritizing the well-being of one’s own children over that of strangers in the developing world) but all moral judgments (e.g., caring about the well-being of other people). If we were solitary animals like tigers, we wouldn’t care about our conspecifics at all. Humans have altruistic feelings because such feelings confer an adaptive advantage to animals that live in complex, structured social groups. EDAs that are leveled against religious belief may similarly overshoot their purpose. Studies on the cognitive science of religion indicate that religious beliefs are byproducts of everyday cognitive capacities, such as agency detection or attribution of design (see e.g., Bloom 2007, for an overview). To some authors the fact that religion is a byproduct of evolved cognitive faculties undermines its epistemic standing. To quote Dawkins (2006 p. 184): ‘The irrationality of religion is a byproduct of a particular built-in irrationality mechanism in the brain.’ But if being a byproduct undermines religious beliefs, one could argue that science, which is also a byproduct of the evolved structure of human cognition, is likewise undermined:

1. We can hold scientific beliefs due to our evolved capacities for understanding the physical, biological, and mental world.
2. Natural selection is not a truth-tracking process.
3. Therefore, scientific beliefs are unjustified.

Note that it does not help much to say that one does not endorse adaptationism, since scientific beliefs formed through cognitive skills that have arisen through drift or other non-adaptive processes would be even less reliable than those formed through natural selection.

Interestingly, it seems that for *any* belief that is plausibly influenced by human cognitive predispositions, one can construct both an EA and an EDA, suggesting that we cannot draw straightforward conclusions from evolutionary origins to epistemic justifications. Take theistic beliefs. Murray (2008) speculates that God has instilled cognitive predispositions in humans through natural selection which elicit religious beliefs in a broad variety of circumstances. By contrast, Dawkins (2006) claims that the evolutionary origin of religious beliefs provides *prima facie* evidence against the existence of God. Or take scientific knowledge. Papineau (2000) asserts that evolution promotes truth-approximating beliefs in scientific practice because of selective pressures that have enhanced human capacities for rational reasoning in the domains of folk psychology and means-end reasoning. On the other hand, Akins (1996) argues that our cognitive faculties are not aimed at a disinterested and objective representation of reality, but rather at forming beliefs that benefit the organism. It seems that evolutionary biological considerations will remain indecisive for the epistemic justification or debunking of scientific beliefs. A single brain cannot test its own reliability without being subject to either circularity (justifying its own working) or debunking (undermining its own reliability). However, if the dynamics of knowledge acquisition in institutionalized environments are very different from those in individual agents, it may be possible for *interacting* brains to do so. In what follows, we consider a pessimistic scenario in which cognitive biases are very influential in science. We will present an analytical model of cultural transmission that shows that interacting scientists are able to overcome these cognitive biases in a broad range of circumstances. Note that, since this is an externalist justification of scientific beliefs, we need not worry about the radically skeptical possibility that our model, like other types of beliefs, might in its turn be subject to cognitive biases. The only thing that is required, from an externalist point of view, is that there *are* mechanisms in the external world that promote the growth of scientific knowledge; scientists need not be aware of these mechanisms.

6 The cultural transmission of scientific knowledge: a model

To examine the cultural transmission of scientific knowledge, we develop an analytical model, based on Henrich and Boyd's (2002) work on biased cultural transmission. Cultural transmission takes place in human minds. It is biased by prior beliefs and expectations. In particular, our model focuses on the role of intuitive ontologies in scientific practice. It does not require high-fidelity copying of cultural traits, nor that these traits are discrete. It does rely on the assumption that scientific models can be more or less truth-approximating. There are well-known objections to this assumption, and a discussion of this falls beyond the scope of this paper. However, given that most defenses of scientific realism seem to require some form

of truth-approximation, the assumption seems quite reasonable. As we shall see, the dynamics of cultural transmission are such that science can evolve progressively even when starting out with very low levels of empirical accuracy; even if initial theories are mostly wrong, they can converge towards more accurate representations over time given a large enough population of scientists and a sufficient level of diversity of inferences.

We start out with a range of scientific ideas that attempt to represent some aspect of reality or that attempt to solve a particular science-related problem. It does not matter whether we talk about the evolution of crustaceans, the structure of the atom, or reasons for the fall of the Roman empire. Assuming ontological realism, not all scientific solutions will capture observer-independent reality equally well. Each scientific model has a z value, a positive real number. Higher z values denote better scientific models, i.e., they are more truth-approximating or more efficient at solving a science-related problem. $\Delta\bar{z}$ is the average change in z across the community of scientists, denoted by N , that is concerned with a particular problem. For example, suppose that z stands for the representational adequacy of models of the structure of the atom that were in the running in the early twentieth century. N would then be the pool of scientists who investigated the structure of the atom in that period. Of the models of the atom that were circulating then, Dalton's early nineteenth-century model of atoms as hard billiard balls had a lower z value than Thomson's plum pudding model of electrons floating in a soup of positive charge which in turn had a lower z value than Rutherford's model of the atom as a miniature solar system. Even though Rutherford's analogy is no longer used in contemporary physics, it still had the highest z value of the aforementioned models, since it made a distinction between the positive nucleus and the negative electrons. $\Delta\bar{z}$ is the shift in representational accuracy from the early nineteenth to the early twentieth century. Since the average representational accuracy of models of the atom improved, $\Delta\bar{z}$ was positive. If there had been scientific stasis (no improvement in these models) $\Delta\bar{z} = 0$; if there had been a decline in scientific accuracy (for instance, if scientists during this period had reverted to a form of ancient Greek atomism), $\Delta\bar{z}$ would have been negative.

To model the transmission of scientific practice, we use the Price equation (Price 1972), which describes changes in the frequency of traits that are transmitted. This equation is widely used in disparate scientific domains, including biology, economics, and anthropology. It models the extent to which transmittable characteristics covary with the effects of selection (first term of Eq. 1), and the rate at which these characteristics change over time (second term). Henrich and Boyd (2002) and Henrich (2004) have adapted it to study the transmission of culturally acquired skills; here we will use it to examine the transmission of scientific knowledge. In a general form the Price equation states:

$$\Delta\bar{z} = \underbrace{\text{Cov}(f, z)}_{\text{selective transmission}} + \underbrace{E(f\Delta z)}_{\text{noisy inference}} \quad (1)$$

Equation 1 describes how the average value of any transmittable trait z changes in a population from one generation to the next. To predict the value of $\Delta\bar{z}$, we need to

take into account on the one hand its selective transmission—in this case, the adoption of a specific scientific model based on its perceived empirical adequacy and instrumental effectiveness by scientific peers—and on the other hand distorting influences of cognitive biases. The former is modeled as $Cov(f, z)$ (covariation of z with its cultural success) and the latter as $E(f\Delta z)$ (expected cultural success of z as it changes over time). f gives the relative likelihood that a given scientific model z will be chosen. We will here assume that scientists are able to assess the merits of scientific models. This model is agnostic as to how people assess competing scientific theories; this can be through epistemic values, intuition, experiment, evaluation of empirical adequacy or a combination of these factors. We also suppose for simplicity's sake that members of the scientific community want to adopt the best scientific model, denoted by z_h . Assuming that members of the scientific community attempt to incorporate the most successful representations of reality z_h , $f_h = 1$ and $f_{not h} = 0$. This reduces Eq. 1 to

$$\Delta \bar{z} = z_h - \bar{z} + \Delta z_h \quad (2)$$

Due to errors inherent in cultural transmission and the effects of cognitive biases, most scientists of N will end up with lower z values than z_h . Henrich and Boyd (2002) model the newly obtained z value as randomly drawn from a Gumbel distribution.² This provides us with a rather pessimistic assumption: there is a greater probability that a scientist who adopts a model will get it wrong, and will end up with a lower z value, typically by an amount α , which represents the systematic biases of our evolved cognitive faculties. However, as in other forms of cultural learning, there are stochastic processes involved, so that some individuals might end up with a higher z value, due to individual learning or even lucky errors. If the new most successful model z_h is accepted by the scientific community, the average z value can exceed the previous mean ($\Delta \bar{z}$ is positive). One could also imagine that members of the scientific community will not end up with a higher z value, or alternatively, that they do not adopt a new model with a high z value. Recall that $\Delta \bar{z}$ can be 0 (scientific stasis), or can even become negative (decline of scientific knowledge). Under what conditions can we expect these scenarios to occur?

Henrich (2004) derived the following equation (see his Appendix A for technical details on the derivation), which we apply to calculate $\Delta \bar{z}$, i.e., the change in z value across time in the population of scientists working on the same problem:

$$\Delta \bar{z} = -\alpha + \underbrace{\beta(\gamma + \ln(N))}_{\text{always positive}} \quad (3)$$

To assess whether scientific progress will be positive, 0 or negative, one needs to take the following variables into account: α , the difference between average z value (\bar{z}) and z_h ; β , the variability of the Gumbel distribution which represents the degree to which scientists will make different inferences; N , the size of the scientific community. γ is the Euler-Mascheroni constant (≈ 0.577). One can see that the first term of Eq. 3 acts against cultural transmission: α represents the effects of low-

² This is a type of extreme probability distribution that models long (finite) sequences of random variables.

fidelity transmission due to cognitive biases. Therefore, it is negative and lowers the value of $\Delta\bar{z}$, except in cases where scientists take over a model without modifying it, in which case $\alpha = 0$. The second term promotes scientific progress. $\ln(N)$ is the natural logarithm of N . We presupposed interaction among the scientific community, so N is the population of interacting scientists. β is a mathematical measure of the tendency of people to make different inferences, in this case, diverging scientific models of the same aspect of reality. For instance, in the early twentieth century, there were several competing models of the structure of the atom, yielding a high β value. Interestingly, the larger β , the higher the chance that models will be invented that exceed the mean of previous z values. In other words, the more scientists make *different* inferences, the more likely scientific progress becomes. In contrast to what some Bayesian philosophers of science contend (see Shaffer 2008, for an overview), this model suggests that disagreement among scientists is not undesirable—quite on the contrary, it is essential for scientific progress.

To obtain a positive $\Delta\bar{z}$ value, one needs a large number of scientists N when cognitive biases α are substantial, or when the tendency to make different inferences β is small. In other words, even if α is disproportionately large, i.e., if human cognitive biases were even further off the mark than they actually are, it is still possible to have scientific progress if scientists make many different inferences and if the scientific community is sufficiently large. The critical value for N , i.e., the minimal number of interacting scientists within a community that is necessary to maintain a given level of scientific knowledge is shown for different values of α/β in the supplementary movie S1. Larger values of α make scientific progress more difficult. As can be seen, larger values of α/β require larger critical values for N . Also, the model predicts that, since the natural logarithm of N plays a role in the value of $\Delta\bar{z}$, disproportionate increases of N are required to maintain the same levels of scientific growth once N gets substantially large. Quantitative studies that link the size of the scientific community and scientific discovery in diverse disciplines are in line with this prediction, including genetics (Glass 1979) and physics (Wagner-Dobler and Berg 1999). In this latter study, one can see, for example, a concurrence between a steep increase in the number of authors working on electricity and magnetism in the mid nineteenth century with important discoveries in that field, such as Maxwell's unification of electricity, magnetism and light into a single theory of the electromagnetic field in the 1860s (Wagner-Dobler and Berg 1999, p. 256).

It should be noted that this model is highly idealized to enhance its conceptual clarity. One of the factors that it does not take into account is luck, i.e., single individuals working in relatively small research communities (e.g., Newton or van Helmont) can produce large improvements by happening to make the right guess. Translated into this model, this would correspond to an initial high z_h value within a small N . The model is not designed to predict the future history of science, but rather to explain factors that mediate scientific progress, including factors in actual historical case studies. In the future, it could be combined with other approaches, such as work that conceptualizes science as an epistemic landscape (e.g., Weisberg and Muldoon 2009).³

³ Thanks to the anonymous reviewer for pointing this out.

7 An illustration: eighteenth- and nineteenth-century transmutation theories

There is no prescribed methodology to assign concrete values to α/β in the growth of scientific knowledge, although it is often possible to get estimations of N . In order to get a qualitative feeling for the predictions of the model, we will apply it to the development of theories on transmutation⁴ of species in biology in the period from 1760 to 1860. Since Antiquity, most naturalistic theories on the origin of species tended to be overwhelmingly (though not exclusively) essentialist. As argued in Sects. 2 and 3, this may be due to the fact that human reasoning about species is biased towards essentialism. Next to this, psychological evidence (e.g., Kelemen 2004) indicates that humans also possess a natural propensity for teleological reasoning. Across cultures, humans have the intuition that animals and plants possess adaptations that are self-beneficial and well-adapted to their environment, such as claws for defense or thorns for protection against being eaten (Barrett 2004). Children and adults with little schooling also have an overwhelming preference for teleological rather than mechanistic or evolutionary explanations. Teleological explanations are at odds with a correct understanding of the evolution of species, because in such accounts the function of a trait provides a necessary and sufficient explanation for its existence (e.g., a giraffe has a long neck in order to reach high foliage) which does not leave room for mechanistic, evolutionary accounts. Additionally, biological evolutionary changes cannot be directly observed, but must be indirectly inferred. In the case of transmutation theories, there is thus a substantial cognitive bias α . To offset the effects of α , natural historians and natural philosophers (terms that denote what we now call biologists) needed a large β and a sizable population of interacting biologists N . The extent to which biological theories on speciation are truth-approximating will be taken as an indicator of their z -value.

Although transmutation theories go back at least to Antiquity, with authors like Empedocles, Anaxagoras, Democritus and Lucretius, it was only from the middle of the eighteenth century onwards that such theories were systematically considered and explored. Contrary to common opinion, Lamarck's and Darwin's were only two among many such ideas (Bowler 2003; Mayr 1982). In Germany at the end of the eighteenth century, members of the so-called Göttingen school, such as Blumenbach, Kiemeier and Reil, stipulated forces that acted on biological entities, in analogy to physical forces acting on physical entities. French naturalists were the first to propose detailed theories of how species can transmute (change) into other species. An early example is de Maillet's *Telliamed, Ou entretiens d'un philosophe indien avec un missionnaire françois* (1748), which proposed that life-forms had spontaneously emerged on Earth, and that their adaptation to diverse circumstances gave rise to distinct species. In his *Histoire naturelle générale et particulière* (vol. 14, 1766) Buffon argued that closely related species, such as horses and donkeys might have a shared common ancestor; evolutionary changes occurred mainly through

⁴ Transmutation is a historical term for what is now denoted by biological evolution which avoids the anachronism of 'pre-Darwinian evolutionary theory'. The term 'evolution' was not routinely used to denote the natural development of life on Earth until Herbert Spencer popularized this sense of the term in the second half of the nineteenth century. Darwin, for example, in his *Origin of species* (1859), only once used the derivative 'evolved'.

degeneration. Lamarck delineated a tree-like structure of the origin of species; he thought that transmutation of species occurred through the transmission of acquired characteristics, an idea developed in detail in his *Philosophie zoologique* (1809). These ideas enjoyed wide currency across Europe, being translated within a few years of publication in several European languages, and were further developed by authors in Italy, Belgium, and the United Kingdom (Corsi 2005). Examples include the Belgian geologist Omalius d'Halloy's *Notes sur la succession des êtres vivants* (1846) and Chambers' progressive notion of transmutation in *Vestiges of the natural history of creation* (1844). Thus, from the mid eighteenth century onwards, there is a burgeoning β value for transmutation theories.

None of these theories would be endorsed by biologists today. Even though they have elements that are correct, they have a lot of assumptions that are now considered to be mistaken. For example, the notion of an inbuilt capacity for striving towards perfection, as marshaled by Lamarck and Chambers, is now uniformly rejected, as are other forms of teleological reasoning in biology. From the perspective of biased cultural transmission, the initial correctness of theories is not important, rather, it is the diversity of the inferences and the size of the scientific community that increase the probability that some of these theories will become more truth-approximating than earlier ones. When more truth-approximating models are adopted by other members of the community, the quality of transmutational theories ratchets upwards. This is in accordance with quantitative data on the size of the scientific community at the time. Shelishch (1982) has made estimates of the community size of active biologists (natural historians and natural philosophers) from 1760 to 1860. His numbers are an underestimation of the true size of the scientific community that was involved, as he only included prolific authors, and did not incorporate authors from related disciplines like the geologist Lyell who were important for the development of transmutation theories. First, there is a slow linear growth in the community of biologists from 1760 to 1790, followed by a steeper growth in almost all biological fields from 1790 to 1860: in 1760, the number of active biologists was about 60, by 1820, it had increased to 160, and in 1860, it had reached 240.

The effects of N on the ability of a scientific community to maintain complex theories is shown in Fig. 1. Here, the Y -axis represents $\Delta\bar{z}$; the X -axis shows the number of biologists N . The logarithmic curves indicate the scientific progress or decline with different values of α/β . The dashed line represents a simpler level of biological theorizing, $\alpha/\beta \approx 4.5$; the full line shows a more advanced level, $\alpha/\beta \approx 6$. The intersections of these curves with the X -axis indicate the critical value of N to maintain particular levels of biological theorizing. As can be seen, a group of 240 interacting naturalists can maintain a more advanced level of scientific knowledge than one of 60.

The model predicts that, given a larger N and a large β , scientific knowledge is likely to be more truth-approximating over time. Is this the case for theories on the transmutation of species? The \bar{z} value of concepts of the transmutation of species increased during the late eighteenth to the mid nineteenth century, as more and more naturalists accepted transmutation and common descent, and started to elaborate on these theories. Even scholars originally opposed to the idea came to make active

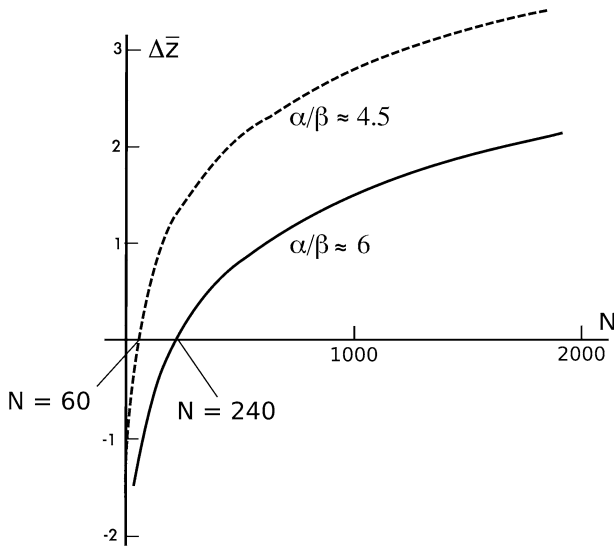


Fig. 1 Relationship between values of N and complexity of biological theory that can be maintained. A community size of 240 active biologists can maintain more complex theories ($\alpha/\beta \approx 6$), compared to a population of 60 biologists ($\alpha/\beta \approx 4.5$)

contributions to them. Richard Owen, for example, initially denied transmutation, but in his *On the nature of limbs* (1849) he argued that humans evolved from fish. In the course of the nineteenth century, these theories also became more accurate than their predecessors. For example, at the turn of the nineteenth century, the issue of extinction was still hotly debated. Some authors, like Lamarck, thought that species do not go extinct but merely evolve into different species. By the 1830s, due to the work of, for instance, Cuvier and Agassiz, the factuality of extinction was no more in question (Herbert 2005). Similarly, the persistence of some types of animals over several geological periods, such as the brachiopod *Lingula*, casted doubt on saltationist and catastrophist models of species origination that were common in the eighteenth century (Mayr 1982).

Historical studies (e.g., Herbert 2005) indicate that Darwin relied extensively on earlier transmutationist theories when conceiving his theory of natural selection. These sources included his own grandfather Erasmus Darwin, Lamarck (likely through the Lamarckian anatomist Robert Grant, who taught him at Edinburgh), Chambers (whose *Vestiges* was immensely popular at the time), and von Baer's embryology, while he also extensively studied critics of earlier transmutationist models. The increasing recognition of the influence of earlier transmutationist theories in Darwin's work supports the importance of scientific community size in scientific practice and discovery. More speculatively, Bowler (2008) has argued that even if Darwin had never written *On the origin of species*, we would likely still have ended up with something like evolutionary theory today. Indeed, transmutation was widely accepted by the mid nineteenth century, and several authors, also building on contemporary literature, came up with elements of natural selection independently

from Darwin. The physician Wells proposed a mechanism akin to natural selection operating across human populations to account for variation in skin color and disease resistance in his posthumously published *An account of a female of the white race of mankind, part of whose skin resembles that of a negro; with some observations on the causes of the differences in colour and form between the white and negro races of men* (1818). Matthew (1831), a timber-merchant who saw the role of random variation in evolutionary change, published this idea almost as an afterthought in Note B (pp. 364–365) and in the final Appendix (pp. 383–385) of his *On naval timber and arboriculture*. In a series of papers, the zoologist and animal trader Blyth (e.g., *An attempt to classify the “varieties” of animals, with observations on the marked seasonal and other changes which naturally take place in various British species, and which do not constitute varieties*, 1835) discerned variation as a causal mechanism to explain why domesticates could revert to their wild types. And, as is well known, Wallace developed his own transmutation theory based on natural selection in two related papers (*On the law which has regulated the introduction of new species*, 1855, and *On the tendency of varieties to depart indefinitely from the original type*, 1858).

The case of the transmutation of species indicates that a large scientific community, combined with an ability to draw many different kinds of inferences, can lead to more truth-approximating theories, even when constrained by cognitive biases, and starting with an initial low accuracy. The analytic model does not guarantee that our current scientific models would be correct. It also allows for the possibility that scientific knowledge declines, for example in the case of a strict orthodoxy that would prevent the generation of many different inferences, or if there were a severe decline in the community size of interacting scientists.

In conclusion, we examined the implications of evolutionary arguments and evolutionary debunking arguments for scientific knowledge. We showed through an analytical model that over time scientific knowledge acquisition can become more truth-approximating under a broad range of conditions. High fidelity of transmission is not necessary, and cognitive biases may be substantial, provided that they are offset by the tendency to make many different scientific inferences and by a large scientific community.

Acknowledgments We would like to thank Igor Douven, Krist Vaesen, and an anonymous reviewer, for helpful comments on an earlier version of this paper, and Lesley De Cruz for help with programming in *Mathematica*. This research is supported by the Research Foundation Flanders and grant COM07/PWM/001 from Ghent University.

References

- Akins, K. (1996). Of sensory systems and the “aboutness” of mental states. *Journal of Philosophy*, 93, 337–372.
- Barrett, H. C. (2004). Design versus descent in Shuar children’s reasoning about animals. *Journal of Cognition and Culture*, 4, 25–50.
- Beauchamp, M. S., Lee, K. E., Haxby, J. V., & Martin, A. (2002). Parallel visual motion processing streams for manipulable objects and human movements. *Neuron*, 34, 149–159.

- Bloom, P. (2007). Religion is natural. *Developmental Science*, 10, 147–151.
- Bonatti, L., Frot, E., Zangl, R., & Mehler, J. (2002). The human first hypothesis: Identification of conspecifics and individuation of objects in the young infant. *Cognitive Psychology*, 44, 388–426.
- Boulter, S. J. (2007). The “evolutionary argument” and the metaphilosophy of commonsense. *Biology & Philosophy*, 22, 369–382.
- Bowler, P. (2003). *Evolution. The history of an idea* (3rd ed.). Berkeley & Los Angeles: University of California Press.
- Bowler, P. (2008). What Darwin disturbed: The biology that might have been. *Isis*, 99, 560–567.
- Boyer, P. (2000). Natural epistemology or evolved metaphysics? Developmental evidence for early-developed, intuitive, category-specific, incomplete, and stubborn metaphysical presumptions. *Philosophical Psychology*, 13, 277–296.
- Bräuer, J., Kaminski, J., Riedel, J., Call, J., & Tomasello, M. (2006). Making inferences about the location of hidden food: Social dog, causal ape. *Journal of Comparative Psychology*, 120, 38–47.
- Brewer, W. F., Chinn, C. A., & Samarapungavan, A. (2000). Explanation in scientists and children. In F. C. Keil & R. A. Wilson (Eds.), *Explanation and cognition* (pp. 279–298). Cambridge, MA: MIT Press.
- Callaghan, T., Rochat, P., Lillard, A., Claux, M. L., Odden, H., Itakura, S., Tapanya, S., & Singh, S. (2005). Synchrony in the onset of mental-state reasoning: Evidence from five cultures. *Psychological Science*, 16, 378–384.
- Chittka, L., & Niven, J. (2009). Are bigger brains better? *Current Biology*, 19, 995–1008.
- Corsi, P. (2005). Before Darwin: Transformist concepts in European natural history. *Journal of the History of Biology*, 38, 67–83.
- Dawkins, R. (2006). *The God delusion*. Boston: Houghton Mifflin.
- De Cruz, H., & De Smedt, J. (2007). The role of intuitive ontologies in scientific understanding—The case of human evolution. *Biology & Philosophy*, 22, 351–368.
- Dennett, D. C. (1991). *Consciousness explained*. London: Penguin.
- Farah, M. J., & Rabinowitz, C. (2003). Genetic and environmental influences on the organization of semantic memory in the brain: Is “living things” an innate category? *Cognitive Neuropsychology*, 20, 401–408.
- Fodor, J. A. (1981). *Representations: Philosophical essays on the foundations of cognitive science*. Cambridge, MA: MIT Press.
- Foley, R. (2001). In the shadow of the modern synthesis? Alternative perspectives on the last fifty years of paleoanthropology. *Evolutionary Anthropology*, 10, 5–14.
- Gallagher, H. L., & Frith, C. (2003). Functional imaging of ‘theory of mind’. *Trends in Cognitive Sciences*, 7, 77–83.
- Gelman, S. A. (2004). Psychological essentialism in children. *Trends in Cognitive Sciences*, 8, 404–409.
- Gelman, S. A., & Wellman, H. M. (1991). Insides and essences: Early understandings of the non-obvious. *Cognition*, 38, 213–244.
- Glass, B. (1979). Milestones and rates of growth in the development of biology. *Quarterly Review of Biology*, 54, 31–53.
- Godfrey-Smith, P. (1991). Signal, decision, action. *Journal of Philosophy*, 88, 709–722.
- Gopnik, A., & Meltzoff, A. (1997). *Words, thoughts and theories*. Cambridge, MA: MIT Press.
- Henrich, J. (2004). Demography and cultural evolution: How adaptive cultural processes can produce maladaptive losses—The Tasmanian case. *American Antiquity*, 69, 197–214.
- Henrich, J., & Boyd, R. (2002). On modeling cognition and culture. Why cultural evolution does not require replication of representations. *Journal of Cognition and Culture*, 2, 87–112.
- Herbert, S. (2005). The Darwinian revolution revisited. *Journal of the History of Biology*, 38, 51–66.
- Hull, D. L. (1964). The effect of essentialism on taxonomy—Two thousand years of stasis. *British Journal for the Philosophy of Science*, 15, 314–326.
- Kahane, G. (in press). Evolutionary debunking arguments. *Noûs*.
- Kelemen, D. (2004). Are children “intuitive theists”? Reasoning about purpose and design in nature. *Psychological Science*, 15, 295–301.
- Leakey, R. E., & Walker, A. C. (1976). *Australopithecus, Homo erectus*, and the single species hypothesis. *Nature*, 261, 572–574.
- Matthew, P. (1831). *On naval timber and arboriculture; with critical notes on authors who have recently treated the subject of planting*. London: Longman, Rees, Orme, Brown & Green.
- Mayr, E. (1982). *The growth of biological thought. Diversity, evolution and inheritance*. Cambridge, MA: Harvard University Press.

- McKay, R. T., & Dennett, D. C. (2010). The evolution of misbelief. *Behavioral and Brain Sciences*, 32, 493–510.
- Miller, R., Owens, S. J., & Rørslett, B. (2011). Plants and colour: Flowers and pollination. *Optics and Laser Technology*, 43, 282–294.
- Millikan, R. (1984). *Language, thought, and other biological categories*. Cambridge, MA: MIT Press.
- Murray, M. (2008). Four arguments that the cognitive psychology of religion undermines the justification of religious belief. In J. Bulbulia, R. Sosis, E. Harris, R. Genet, C. Genet, & K. Wyman (Eds.), *The evolution of religion: Studies, theories, and critiques* (pp. 393–398). Santa Margarita: Collins Foundation Press.
- Osawa, A., & Maeshima, S. (2009). Gerstmann's syndrome in a patient with left thalamic hemorrhage. *Neurology Asia*, 14, 161–164.
- Papineau, D. (2000). The evolution of knowledge. In P. Carruthers & A. Chamberlain (Eds.), *Evolution and the human mind. Modularity, language and meta-cognition* (pp. 170–206). Cambridge: Cambridge University Press.
- Pinker, S. (2005). So how does the mind work? *Mind and Language*, 20, 1–24.
- Plantinga, A. (1993). *Warrant and proper function*. Oxford: Oxford University Press.
- Price, G. (1972). Extension of covariance selection mathematics. *Annals of Human Genetics*, 35, 485–490.
- Quine, W. V. O. (1969). *Ontological relativity and other essays*. New York: Columbia University Press.
- Real, L. A. (1991). Animal choice behavior and the evolution of cognitive architecture. *Science*, 253, 980–986.
- Reid, T. (1764). *An inquiry into the human mind, on the principles of common sense*. Edinburgh: Millar, Kincaid & Bell.
- Rowlands, M. (1997). Teleological semantics. *Mind*, 106, 279–303.
- Samarapungavan, A., & Wiers, R. W. (1997). Children's thoughts on the origin of species: A study of explanatory coherence. *Cognitive Science*, 21, 147–177.
- Saxe, R., Tenenbaum, J., & Carey, S. (2005). Secret agents: Inferences about hidden causes by 10- and 12-month-old infants. *Psychological Science*, 16, 995–1001.
- Shaffer, M. (2008). Bayesianism, convergence and social epistemology. *Episteme*, 5, 203–219.
- Shtulman, A., & Schulz, L. (2008). The relation between essentialist beliefs and evolutionary reasoning. *Cognitive Science*, 32, 1049–1062.
- Shelishch, P. B. (1982). A quantitative study of biologists in the 18th and 19th centuries. *Scientometrics*, 4, 317–329.
- Shultz, T. R. (1982). Causal reasoning in the social and nonsocial realms. *Canadian Journal of Behavioural Science*, 14, 307–322.
- Spelke, E. S., Phillips, A., & Woodward, A. L. (1995). Infants' knowledge of object motion and human action. In D. Sperber, D. Premack, & A. J. Premack (Eds.), *Causal cognition. A multidisciplinary debate* (pp. 44–78). Oxford: Clarendon Press.
- Stamos, D. N. (2005). Pre-Darwinian taxonomy and essentialism—A reply to Mary Winsor. *Biology & Philosophy*, 20, 79–96.
- Stephens, C. L. (2001). When is it selectively advantageous to have true beliefs? Sandwiching the better safe than sorry argument. *Philosophical Studies*, 105, 161–189.
- Stewart-Williams, S. (2005). Innate ideas as a naturalistic source of metaphysical knowledge. *Biology & Philosophy*, 20, 791–814.
- Sullivan, P. R. (2009). Objects limit human comprehension. *Biology & Philosophy*, 24, 65–79.
- Wagner-Dobler, R., & Berg, J. (1999). Physics 1800–1900: A quantitative outline. *Scientometrics*, 46, 213–285.
- Waxman, S. (2005). Why is the concept 'living thing' so elusive? Concepts, languages, and the development of folkbiology. In W. K. Ahn, R. L. Goldstone, B. C. Love, A. B. Markman, & P. Wolff (Eds.), *Categorization inside and outside the laboratory. Essays in honor of Douglas L. Medin* (pp. 49–67). Washington: American Psychological Association.
- Weisberg, M., & Muldoon, R. (2009). Epistemic landscapes and the division of cognitive labor. *Philosophy of Science*, 76, 225–252.