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Bundles of Contradiction

A COEXISTENCE VIEW OF CONCEPTUAL CHANGE

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INTRODUCTION

Why do giraffes have long necks? One idea is that they were given long necks by a divine creator. Another is that they acquired long necks by stretching their necks day after day, week after week, year after year. And yet another is that giraffes that were randomly born with longer necks were more successful at surviving and reproducing in the African savanna and thus passed on an inherent disposition for long necks to their offspring.

The diversity of views on why giraffes have long necks is not special or unusual. Any phenomenon is consistent with multiple theories, and alternative theories often coexist. Scholars interested in the development of conceptual understanding have generally neglected this fact: The process of conceptual change, or knowledge acquisition at the level of individual concepts, has traditionally been framed as the transition from an inaccurate, intuitive theory of a domain to a more accurate, scientific theory of that domain, without much attention to the diversity of views that may abound even *after* the transition (Carey, 1985; Vosniadou, 1994). In other words, it has typically been assumed that, in any given domain, the endpoint of conceptual change is acquiring a scientific theory of the domain, and that scientific theories replace the nonscientific theories that came before them. Recent research, however, has begun to show that nonscientific theories persist in the minds of scientifically literature adults, coexisting and sometimes competing with scientific alternatives. We refer to this phenomenon as *explanatory coexistence* (see also Gelman, 2011; Legare, Evans, Rosengren, & Harris, 2012).

Explanatory coexistence poses a strong challenge to traditional notions of conceptual change because it implies that concepts do not always *change*; they sometimes proliferate. While it's long been argued that scientific concepts do not "replace" nonscientific concepts in the sense of merely overwriting them (Caravita & Halldén, 1994; Spada, 1994), all dominant models of conceptual change assume replacement in the sense that structures existing before the change cease to exist following the change. Put differently, models of conceptual change that link parent concepts to their descendant concepts through some form of transformation—whether it be differentiation and coalescence (Carey, 1999), ontological reclassification (Chi, 2005), or the reanalysis of core presuppositions (Vosniadou, 1994)—entail an implicit process of replacement, albeit one that occurs over an extended time frame and with many intermediate steps. Descendant concepts are assumed to replace the parent concepts, not live side by side with those concepts, potentially competing with them for explanatory dominance.

In this chapter, we review evidence for explanatory coexistence obtained through a variety of methods and across a variety of domains, with theories of biological adaptation as a recurring illustration. We then consider four explanations for why nonscientific theories could persist in the face of scientific ones, arguing that they are most likely preserved for their lasting cognitive utility. Folk theories, after all, serve multiple and sometimes competing aims, not unlike competing scientific models within a given field of science at a given point in time. We conclude by noting important implications of explanatory coexistence for future research on conceptual change.

Our focus throughout the chapter is on cases of explanatory coexistence in which the coexisting explanations are mutually incompatible; that is, they derive from theories that carve up the same domain of phenomena into different ontological categories and define different operations over those categories. There are certainly cases in which we hold multiple, *complementary* explanations of the same phenomena—for example, multiple explanations of why underprivileged students often perform poorly in school or multiple explanations of why former convicts often return to crime (Kuhn, 1991)—but those cases do not require special explanation from a conceptual point of view. Likewise, the fact that two explanations are mutually incompatible does not mean that the theories that generated those explanations are globally incommensurable (Carey, 1999); they most certainly overlap in their conceptual structures and conceptual referents or they would not be considered theories of the same domain. Our objective, then, is not to argue that all competing explanations are incommensurate or that all incommensurate explanations are irreconcilable, but to argue that some of the explanations we treat as viable accounts of the same phenomena are incommensurate and that such explanations bely the existence of qualitatively different theories, many of which we have explicitly rejected or abandoned earlier in development.

TWO FLAVORS OF EXPLANATORY COEXISTENCE

Coexistence between scientific and nonscientific theories comes in at least two flavors. One is the coexistence of scientific and *supernatural* theories of the same domain. In the domain of biology, for instance, evolution by natural selection and creationism both offer explanations for the origin and complexity of adaptive traits. Creationist beliefs have been documented not only among religious fundamentalists, who explicitly avow such beliefs, but also among secular children and adults, who do not explicitly avow such beliefs but sometimes implicitly appeal to creation when asked to explain where living creatures came from (Evans, 2001; Samarapungavan & Wiers, 1997). Similarly, nondenominational arguments for the "intelligent design" of biological organisms have resonated with the general public for centuries and continue to resonate with the general public today, despite increased exposure to the scientific alternative of evolution by natural selection (Lombrozo, Shtulman, & Weisberg, 2006; Tracy, Hart, & Martens, 2011).

The coexistence of scientific and supernatural explanations of the same phenomena is prevalent in other domains as well. Scientific beliefs about the neural basis of cognition and behavior compete with supernatural beliefs about souls to explain consciousness (Preston, Ritter, & Hepler, 2013; Richert & Harris, 2008). Scientific beliefs about the interpersonal transmission of microscopic germs compete with supernatural beliefs about karma and witchcraft to explain illness (Legare & Gelman, 2008; Raman & Gelman, 2004). And scientific beliefs about the interrelated functions of vital organs compete with supernatural beliefs about the afterlife and divine justice to explain death (Harris & Giménez, 2005; Rosengren et al., 2014). While some people have devised explicit means of reconciling these two types of explanations (e.g., positing germs as a proximate cause of illness and witchcraft as a distal cause), many have not (Legare et al., 2012; Legare & Visala, 2011). Instead, they vacillate between scientific and supernatural explanations depending on the events being explained (e.g., the act of thinking vs. the act of feeling; Richert & Harris, 2008, mundane vs. life-altering events, Lupfer, Brock, & DePaola, 1992; Lupfer, Tolliver, & Jackson, 1996) or the context in which the explanation is provided (e.g., a hospital vs. a church; Harris & Giménez, 2005).

Another type of coexistence is that between scientific and *intuitive* theories of the same phenomena, where the intuitive theories deviate from scientific consensus but do not invoke the supernatural. For instance, many adults who have obtained college-level instruction in biology, and who passed those courses with high marks, still appear to hold an intuitive theory of evolution on which evolution is construed as the cross-generational transformation of a species' underlying nature, or "essence," with each organism predisposed to produce offspring more adapted to its environment than it was itself at birth. Natural selection plays no role in this theory, as species are construed not as populations of unique individuals but as discrete types that evolve as homogenous units (Shtulman, 2006). These nonscientific conceptions of evolution are internally consistent and explanatorily broad (Shtulman & Calabi, 2012, 2013).

Coexistence between scientific and intuitive theories is evident in many other domains as well. Adults who have successfully completed college-level instruction in mechanics often maintain intuitive theories of motion predicated on the belief that objects in motion possess an internal force, or "impetus," that will maintain the object's motion until dissipated or transferred to another object (Halloun & Hestenes, 1985; McCloskey, 1983). Adults who have successfully completed college-level instruction in thermodynamics often maintain intuitive theories of heat predicated on the belief that heat is a kind of substance that flows in and out of objects and can be trapped or contained (Chiou & Anderson, 2010; Reiner, Slotta, Chi, & Resnick, 2000). And adults who have successfully completed college-level instruction in astronomy often maintain intuitive theories of the seasons predicated on the belief that the Earth is closer to the sun during summer than it is during winter (Lee, 2010; Tsai & Chang, 2005). In all such cases, adults who have demonstrated mastery of scientific concepts in formal contexts (e.g., problem sets, multiple-choice tests) still tend to default to naïve concepts in informal contexts (e.g., drawing tasks, thought experiments, open-ended explanations).

We should note that explanatory coexistence is not intrinsically tied to holding a *scientific* theory of a domain, where we use "scientific" to denote the theories of contemporary science, not the broader category of those that are naturalistic or differentiated from pseudoscience via some demarcation criterion, such as falsifiability (Hansson, 2015). One could endorse mutually incompatible explanations such that neither explanation is scientific, as in the case of someone who endorses both creationist explanations for the origin of life and evolutionary, yet non-Darwinian, explanations (Shtulman, 2006), or in the case of someone who endorses both witchcraft-based explanations for illness and contagious, yet nonmicrobial, explanations (Solomon & Cassimatis, 1999). There is nothing, in principle, that elevates the conflict between scientific and nonscientific theories above that of two nonscientific theories with regard to the issues considered later in the chapter. Still, conflicts between scientific and nonscientific theories constitute the clearest cases of explanatory coexistence, and we will focus on those cases for that reason. We should also note that we use the term "theory" to refer to networks of causal-explanatory beliefs that have the same structural and functional properties as scientific theories, regardless of whether those beliefs are introspectively accessible and regardless of whether those beliefs are explicitly endorsed.

EVIDENCE OF EXPLANATORY COEXISTENCE

Over the past decade, evidence of explanatory coexistence has been accumulating from a variety of sources: priming tasks, inference tasks, speeded-reasoning tasks, neuroimaging studies, and studies of Alzheimer's patients. These findings paint a less uniform picture of conceptual development and conceptual change than that assumed by previous work in the field.

Scientific vs. Supernatural Theories

Perhaps the most straightforward demonstration of coexistence comes from studies in which adults are asked to evaluate multiple explanations for the same phenomenon or event, such as illness (Legare & Gelman, 2008; Raman & Gelman, 2004) or death (Astuti & Harris, 2008; Harris & Giménez, 2005). Rather than endorse only scientific explanations or only supernatural explanations, most adults endorse a combination of the two. Legare and Gelman (2008), for instance, asked Sesotho-speaking adults in South Africa to evaluate the likelihood that a hypothetical case of AIDS was caused by biological factors, such as blood mixing or unprotected sex, or supernatural factors, such as witchcraft or ancestral displeasure. They found that most adults endorsed both types of factors, despite demonstrating high levels of understanding of the causal properties of AIDS and of AIDS transmission. Similar results have been obtained when adults are asked to evaluate explanations for interpersonal events, such as getting a new job or fighting with one's spouse; individuals who endorse folk psychological explanations *also* frequently endorse supernatural explanations for the same event (e.g., the influence of God), particularly when those events are life-altering (Lupfer et al., 1992, 1996).

Even adults who endorse only scientific explanations for natural phenomena show evidence of representing supernatural explanations at an implicit level. For instance, Preston and colleagues have manipulated adults' implicit evaluation of God relative to science (Preston & Epley, 2009) and their implicit evaluation of the soul relative to the body (Preston et al., 2013) by exposing participants to material intended to prime either religious or scientific conceptions of the same phenomenon. In one such study, participants read a passage about the Big Bang that ended with a statement that either affirmed or challenged the theory's validity. They then completed a speeded categorization task in which they categorized words as positive or negative, sometimes preceded by the words "science" or "God" as masked primes (i.e., "science" or "God" were presented for 15 milliseconds following the 250-millisecond presentation of a mask, such that participants were unaware of the prime). Participants who read the science-affirming statement were faster to classify positive words than negative words when they were preceded by the "science" prime relative to the "God" prime, whereas participants who read the science-challenging statement showed the opposite pattern. Priming participants with religious materials had equivalent effects; when participants were prompted to think of God as an entity with broad explanatory scope, they had more positive implicit associations with God relative to science (Preston & Epley, 2009; see also Tracy et al., 2011).

Coexistence between scientific and supernatural explanations has been revealed using other measures as well. In a study of implicit dualism, Bering (2002) asked adults to determine whether each of 24 bodily states ceased upon death. He found that it took longer for participants to affirm the cessation of psychological states, such as wanting or knowing, than to affirm the cessation of physiological states, such as feeling hungry or feeling sick, even for participants who explicitly disavowed the possibility of an afterlife. In a study of implicit superstition, Subbotsky (2010) showed adults a small wooden box that, when activated by a "magic spell," appeared to damage a stamp placed inside it. While all adults denied that the box was causally efficacious, claiming instead that the outcome they had witnessed was merely an illusion, a third refused to place their driver's licenses inside the box, and two-thirds refused to place their passport inside. On the face of it, this type of competition between implicit and explicit beliefs about a given phenomenon may seem like an alternative to coexistence, as participants' scientific and supernatural theories do not appear to exist harmoniously side by side. Nonetheless, these findings show that the same individuals must in fact represent both sets of beliefs in order for them to compete.

Scientific vs. Intuitive Theories

The primary source of evidence for the coexistence of scientific and intuitive theories is the finding, replicated in many studies, that adults' verification of scientific information takes longer, and is less accurate, the more that information conflicts with intuitive theories of the same domain. When asked to classify entities as alive or not alive, for example, adults are slower to classify plants as alive than to classify animals as alive, presumably because our intuitive theories of life exclude plants (and other seemingly inanimate organisms) from the category *living thing* (Babai, Sekal, & Stavy, 2010; Goldberg & Thompson-Schill, 2009). When asked to predict which of two objects will sink faster in water, adults are slower to make predictions based on density (as represented by the object's material of composition) than to make predictions based on size, presumably because our intuitive theories of matter do not treat density as a separate dimension from weight and size (Kohn, 1993; Potvin, Masson, Lafortune, & Cyr, 2015). And when asked to identify scientifically unwarranted explanations under time pressure, adults are less accurate in rejecting unwarranted teleological explanations (e.g., "trees produce oxygen so that animals can breathe") than in rejecting unwarranted mechanical explanations (e.g., "zebras have black stripes because they eat coal"), perhaps because our intuitive theories of function apply promiscuously to both artifacts and natural kinds (Kelemen, Rottman, & Seston, 2013).

In one of the most systematic demonstrations of this effect, Shtulman and Valcarcel (2012) asked college-educated adults to verify, as quickly as possible, statements of two types: those whose truth-value was the same on both scientific and intuitive theories of a domain (e.g., "the moon revolves around the Earth," which is both scientifically and intuitively true) and those involving the same conceptual relations but whose truth-value differed across scientific and intuitive theories (e.g., "the sun revolves around the Earth," which is intuitively true but scientifically false). The statements covered five concepts in each of ten domains. Consistent with prior studies, they found that intuition-inconsistent statements were verified more slowly and less accurately than intuition-consistent statements, and this effect was obtained in all ten domains: astronomy, evolution, fractions, genetics, germs, matter, mechanics, physiology, thermodynamics, and waves. These results have been replicated among science professors, who are significantly more *accurate* than college undergraduates at verifying intuition-inconsistent statements but are no faster at doing so (Shtulman & Harrington, 2016).

The simultaneous representation of scientific theories and intuitive theories is evident not only in the speed of adults' scientific inferences but also in the content of their errors. For example, when adults are asked to estimate the pairwise distances between international cities, their estimates are typically more consistent with a flat Earth than with a spherical Earth (Carbon, 2010). When adults are asked to recollect the location of a ball 20 ms after it was shot through a spiral tube, their recollections are typically more consistent with a physically impossible spiral path than with the straight path it actually took (Freyd & Jones, 1994). And when adults are asked to indicate where in a sandbox someone will search for a displaced object, their estimates are typically distorted away from where the object was initially buried—and where the digger presumably thinks it is—toward the site of its actual location (Sommerville, Bernstein, & Meltzoff, 2013).

Admittedly, these data constitute only indirect evidence of explanatory coexistence, as there are potentially other ways to explain discrepancies in the speed and accuracy of participants' reasoning across the conditions reported earlier (e.g., the persistence of subconceptual elements rather than conceptual ones, or conflicts within a theory rather than between theories). Nevertheless, at least two considerations suggest that these data comprise more than just a collection of experimental artifacts: (1) their consistency across tasks, materials, and domains and (2) their convergence with findings obtained using fundamentally different methods (fMRI) and in fundamentally different populations (Alzheimer's patients).

With respect to this second consideration, Dunbar, Fugelsang, and Stein (2007) found that college-educated adults exhibited different patterns of brain activity when watching motion displays that were either consistent or inconsistent with the laws of physics. The physics-consistent displays depicted two balls of unequal size falling to the ground at the same rate; the physics-inconsistent displays depicted the larger ball falling to the ground at a faster rate than the smaller ball. Dunbar et al. found that, among participants who judged the physics-consistent displays as natural and the physics-inconsistent displays as unnatural, the act of watching such displays yielded increased activation in the anterior cingulate cortex, an area associated with error detection and conflict monitoring. That is, participants who exhibited no behavioral evidence of the misconception "heavier objects fall faster than lighter ones" still exhibited neural evidence of detecting and inhibiting such a misconception. Similar results have been documented in the domain of electricity, where experts show increased activation in the anterior cingulate cortex, among other areas associated with conflict monitoring, when evaluating electric circuits that are intuitively correct but scientifically impossible (Masson, Potvin, Riopel, & Foisy, 2014).

Finally, studies with Alzheimer's patients provide some of the most direct evidence of the long-term resilience of intuitive theories. Whereas healthy adults reveal only implicit evidence of intuitive theories (in the speed and accuracy of their scientific inferences), Alzheimer's patients reveal explicit evidence of such theories, willingly endorsing explanations for natural phenomena that are typically endorsed only by children. Lombrozo, Kelemen, and Zaitchik (2007), for instance, provided Alzheimer's patients with both mechanistic and teleological explanations for a variety of natural phenomena, some of which warranted a teleological explanation (e.g., eyes exist "so that people and animals can see") and some of which did not (e.g., rain exists "so that plants and animals have water for drinking and growing"). Compared to healthy elderly adults, Alzheimer's patients were more likely to judge unwarranted teleological explanations as acceptable. They were also more likely to judge those explanations as *preferable* to mechanistic ones. Likewise, Zaitchik and Solomon (2008) asked Alzheimer's patients to judge the life status of various entities and found that many based their judgments on the entity's capacity for motion, denying that plants are alive but claiming that the sun and the clouds are alive. The cognitive impairments wrought by Alzheimer's disease seemingly allow intuitive theories that had previously been dominated by scientific theories to manifest in more explicit forms.

EXPLANATIONS FOR EXPLANATORY COEXISTENCE

Having established the robustness of explanatory coexistence across tasks and across domains, we now turn to the question of *why* nonscientific theories survive the acquisition of a scientific alternative. We consider four possibilities: (1) that nonscientific theories persist only insofar as their replacement by a scientific theory is incomplete, (2) that nonscientific theories persist in a vestigial state owing to their connection to less malleable aspects of cognition or perception, (3) that nonscientific theories persist because they reside in aspects of cognitive architecture that are resistant to explicit instruction, and (4) that nonscientific theories persist because of their lasting cognitive utility. While we view the fourth possibility as most promising, we acknowledge that more than one possibility could be true, not just in the sense that a given theory might have some replaced components or some vestigial components, but more generally in the sense that there might be different explanations for explanatory coexistence in different cases.

Incomplete Replacement

One way to explain explanatory coexistence is to challenge the idea that scientific and nonscientific theories truly *co*exist as separate, discrete theories. One could argue, for instance, that the studies cited earlier do not provide evidence of two logically distinct theories, but instead provide evidence of one globally incoherent theory—a theory that contains aspects of both scientific and nonscientific frameworks. Put differently, *parts* of a nonscientific theory may coexist with *parts* of a scientific theory in a transitional state on the way to proper scientific understanding. On this view, explanatory coexistence is a byproduct of imperfect learning; scientific theories do, in fact, replace nonscientific theories, but many learners have acquired only a subset of the relevant scientific concepts, analogous to beginning the process of repainting one's house but stopping midway through. As a result, our conceptual understanding of many domains may be chimeric and would presumably remain chimeric if no further learning occurred.

Clearly, learners vary in their mastery of scientific theories, but it's not obvious that learning those theories is a zero-sum process, with each scientific concept acquired at the cost of a nonscientific concept. Indeed, part of what makes learning many scientific theories difficult is that concepts in those theories bear no direct correspondence to the concepts in nonscientific theories and vice versa (Carey, 1999). The two theories carve up the same domain in qualitatively different ways. More importantly, competition between scientific and nonscientific theories is observed not only in adults who have a tenuous grasp of the scientific theory but in domain experts as well. Under speeded conditions, professional biologists reveal animistic intuitions of the same sort revealed by non-biologists (e.g., that the sun in alive and that plants are not; Goldberg & Thompson-Schill, 2009), and professional physicists endorse unwarranted teleological explanations of the same sort endorsed by non-physicists (e.g., that rain exists so that animals have water for drinking; Kelemen et al., 2013). Likewise, Shtulman and Harrington (2016) found that science professors with three or more decades of career experience were no faster to verify intuition-inconsistent scientific statements than were the students in their courses. For these reasons, the "incomplete replacement" account is itself incomplete.

Vestigial Structures

A different explanation for explanatory coexistence grants that scientific and nonscientific conceptions of a domain are represented as discrete theories, but posits that the nonscientific conceptions are a kind of vestigial structure, rendered irrelevant by the scientific conceptions but preserved nonetheless in much the same way that evolution has preserved nonfunctional structures like the human appendix and the human tailbone. On one version of this account, nonscientific theories are preserved because they are outgrowths of a more foundational form of cognition: core knowledge (Carey & Spelke, 1996; Mahon & Caramazza, 2011). *Core knowledge* is the label given to our innate repertoire of conceptual structures supported by systems of perception that take sensory data as their input and produce conceptual primitives—for example, *agent, object, number*—as their output. If our first theories of a domain arise directly from core knowledge, then core knowledge may be what preserves them past their obsolescence if core knowledge itself remains constant throughout the lifespan. Other versions of this account could be modeled on alternative cognitive architectures that share a commitment to mental structures that are relatively stable across the lifespan, such as some versions of "massive modularity" (e.g., Cosmides & Tooby, 1992).

While it is unclear whether the "vestigial structure" account is neurologically plausible—the brain, after all, tends to be a rampant pruner of unutilized connections

(Luo & O'Leary, 2005)—there are other, theoretical reasons to doubt it. For starters, the core knowledge version of this account assumes that ontological categories and causal mechanisms implicated in nonscientific theories are the same as (or at least firmly rooted in) those available to the newborn infant, yet this is implausible for many nonscientific theories. Intuitive theories of evolution are based on the core ontology of *species* and the core causal mechanisms of *reproduction* and *inheritance* (Shtulman, 2006). Intuitive theories of astronomy are based on the core ontology of *planet* and the core causal mechanisms of *rotation* and *occlusion* (Vosniadou & Brewer, 1994). And supernatural theories of illness are based on the core ontology of *contagion* and the core causal mechanisms of *immanent justice* and/or *witchcraft* (Legare & Gelman, 2008). Certainly, core knowledge supports the acquisition of nonscientific theories, as it supports the acquisition of *all* subsequent knowledge, but the relation between core knowledge and nonscientific theories may be no more intimate than the relation between core knowledge and scientific theories. *Both* types of theories constitute inferential constructions that transcend the representational resources of core knowledge (see Carey & Spelke, 1996).

Architectural Autonomy

A third explanation for coexistence could appeal to dual-process models of cognitive architecture (Evans, 2008), one version of which might claim that nonscientific theories are preserved by virtue of their close relation to "System 1" reasoning, or reasoning based on heuristics and associations (Kahneman, 2011). Scientific theories, in contrast, find a more natural home in System 2, which involves more explicit representations that support conscious reasoning. If System 1 is relatively impervious to explicit instruction of the kind that's typical of science education, one might expect System 1 theories to maintain elements of their nonscientific predecessors, even as System 2 takes up such theories. Put differently, if nonscientific theories are a product of System 1 reasoning and scientific theories are a product of System 2 reasoning, then their coexistence may be a specific instance of the more general observation that System 1 and System 2 themselves coexist.

However, just as the *content* of nonscientific theories differs substantively from the content of core knowledge, the *structure* of nonscientific theories differs substantively from the structure of System 1's architecture. System 1 is a collection of processes characteristically described as "unconscious," "implicit," "automatic," "rapid," "holistic," "perceptual," and "associative." System 2, on the other hand, is a collection of processes characteristically described as "conscious," "explicit," "controlled," "analytic," "reflective," and "rule-based" (Evans, 2008). The two coexist in the sense that they are architecturally (and, hence, computationally) distinct. It's not obvious, however, that scientific and nonscientific theories fit that same dichotomy, that is, that nonscientific theories are more "implicit," "holistic," and "associative" than are scientific theories (see Evans & Lane, 2011). Numerous studies have shown that nonscientific theories have a logic of their own—a logic that is, on the one hand, qualitatively distinct from the logic of the corresponding scientific theory but is, on the other hand, qualitatively similar to the logic of earlier theories in the history of science (Carey, 1999). Historical scientists such as Aristotle, Galileo, Ptolemy, and Lamarck have been accused of many things, but producing merely "associative" or holistic theories is usually not among them.

That said, our prior remarks about the heterogeneity of explanations for coexistence is pertinent to this discussion, as we have much stronger evidence that some nonscientific conceptions are theory-like than we do for others. For instance, we have good evidence that nonscientific conceptions of biological adaptation are theory-like (Shtulman, 2006), but it may be that implicit opposition between science and religion (Preston & Epley, 2009; Tracy et al., 2011) reflects System 1–style associations rather than coherent, explanatory theories that are actively endorsed. In short, the general case for subsuming nonscientific theories under System 1 architecture is unconvincing, but dual-processing accounts could play an explanatory role in a subset of cases.

Differential Utility

The "vestigial structures" and "architectural autonomy" accounts assume that there is something special about the content or format of nonscientific theories that preserves their representation past their obsolescence. We turn now to the possibility that nonscientific theories never become obsolete, and instead remain inferentially useful even in the presence of a more globally accurate scientific theory. Nonscientific theories clearly have utility; if they did not, they would never have been constructed in the first place. What prompts the construction of nonscientific theories is typically the need to explain, predict, or control the phenomena present in one's everyday life: the day–night cycle (Vosniadou & Brewer, 1994), changes of the seasons (Tsai & Chang, 2005), projectile motion (McCloskey, 1983), sinking and floating (Kohn, 1993), eating and growing (Carey, 1985), death and dying (Astuti & Harris, 2008), and so on. The ontological distinctions and causal mechanisms posited to explain those phenomena do an adequate job in many situations. In fact, in some situations, nonscientific theories may provide a more efficient route to the same explanation or prediction that a scientific theory would provide.

Consider, for instance, the task of explaining why giraffes have long necks. On an intuitive theory of evolution, all one needs to determine is how having a long neck is helpful to an individual giraffe in its current environment, whereas on a scientific theory, one needs to consider what traits ancestral giraffes may have possessed, what kinds of selection pressures those traits were under, what kinds of metabolic costs those traits imposed, what kinds of genetic constraints those traits were under, and so forth. In this case, the application of the scientific theory may not only be harder but only yield more useful explanations in a subset of cases, as the additional factors known to be relevant in general are often unknown in their particulars. Or consider theories of home heat control. Many people hold an incorrect theory of how their thermostat works: a "valve theory" as opposed to a "feedback theory" (Kempton, 1986). Having an inaccurate theory may be a problem from an engineering perspective (if, for example, you need to repair a broken system), but it can be highly functional in many day-to-day cases and may even lead to better management of a home heating system than the accurate theory if the application of that theory fails to take many additional factors into account, such as uneven heat distribution and drafts.

These are, of course, simplified examples, but they illustrate the more general point that different theories are useful for making different kinds of inferences, and we likely retain any theory that has sufficient cognitive utility (see Ohlsson, 2009). Just as individuals who know multiple languages often resort to a nondominant language for completing tasks initially learned in that language and still adequately performed in that language (Kolers, 1968), individuals who have acquired multiple theories may resort to nonscientific theories for making inferences first covered by those theories and still adequately derived from those theories. Retaining multiple theories would yield many redundant representations, but the brain does not appear to eschew redundancy. Redundancy is, in fact, a hallmark of perception (Attneave, 1954). We make use of redundant cues to depth (e.g., linear perspective, retinal disparity, motion parallax), redundant cues to object individuation (e.g., local geometry, luminance contrasts, spatiotemporal cohesion), and redundant cues to speech segmentation (e.g., phonotactic constraints, transitional probabilities, changes in prosody). Some cues are more informative than others (e.g., motion parallax is a more informative cue to depth than interposition), and some cues may be more ubiquitous than others (e.g., luminance contrasts are a more ubiquitous cue to objecthood than Gestalt principles), but that does not cause us to lose sensitivity to the less informative or less ubiquitous cues. We retain sensitivity to any cue that may help us disambiguate ambiguous input. Analogously, in the case of induction, we likely retain any theories that help us explain the unexplained or predict the unknown. Accurate inductions are, of course, preferred to less accurate ones, but accuracy is only one consideration that determines a theory's utility; ease of access, ease of application, and simplicity are others (Lombrozo, 2012; Samarapungavan, 1992).

Differential Utility: Further Questions

If the coexistence of scientific and nonscientific theories is construed in terms of differential utility, then this type of coexistence is fundamentally similar to the coexistence of two or more scientific theories in the same field of science—for example, caloric vs. kinetic theories of heat, gradualist vs. catastrophic theories of mass extinctions, orbital vs. cloud models of atomic structure, or symbolic vs. connectionist models of cognitive architecture. In some cases, these theories stand in direct opposition to one another, as is typical of the competition that precedes a paradigm shift (Kuhn, 1977), but in other cases the theories are distinct yet complementary. Weisberg (2007), for instance, notes that scientists often create idealized models of the same phenomenon in order to accomplish different inferential goals. Some idealizations render a model more computationally tractable, some idealizations highlight the core factors that contribute to the phenomenon in question, some idealizations maximize a theory's predictive power, and so on. Often, no one idealization is globally superior to the others. Rather, idealization can be a process of making tradeoffs among competing desiderata such as accuracy, generality, simplicity, and completeness. The relation between scientific and nonscientific theories could be viewed in a similar light: Nonscientific theories are not necessarily flawed, but are instead optimized for making certain kinds of inferences that scientific theories are not.

Admittedly, this account of explanatory coexistence makes the task of explaining theory-based inference more complicated, and it raises a number of important questions for future research. First, how do individuals coordinate two or more active, yet qualitatively distinct, theories of the same domain? Do the concepts in competing theories interact, and if so, how? Redundancy is not, in and of itself, a useful property of mental representation, as redundancy could yield conflict as often as it yields efficiency. The challenge of coordinating different theories may actually introduce a limit on their proliferation, thus helping to explain why we often see more than one for a given phenomenon but rarely see more than a few.

Second, is there an important difference between the two flavors of coexistence identified here: that between scientific and supernatural theories on the one hand, and scientific and intuitive theories on the other? It could be that natural and supernatural theories are coordinated in unique ways given their different epistemic and metaphysical commitments—perhaps, for example, people have an easier time compartmentalizing them as "nonoverlapping magisteria" (Gould, 1997; see also Legare & Visala, 2011) or treat supernatural beliefs as more limited in scope of application and less susceptible to evidence than naturalistic alternatives (Van Leeuwen, 2014). Yet coexistence can also occur even among different supernatural theories (e.g., Barrett & Keil, 1996) or among different intuitive theories (e.g., Vosniadou & Brewer, 1994). Whether the story of coexistence will be similar across these diverse cases is an open question.

Third, is there something special about the coexistence of conceptual structures in the form of theories as compared to other forms of representation, such as semantic associations or prototypes? Given their unique roles in induction and explanation, we speculate that only theories are subject to the particular tradeoffs encountered in scientific modeling (Weisberg, 2007). Just as scientific models must balance potentially competing aims of achieving tractability, accuracy, generality, simplicity, and so on, folk-theoretic explanations aim to balance fit to data, simplicity, scope, and other explanatory virtues (Lombrozo, 2012), as well as pragmatic aims like speed of access and ease of use. So while redundancy and problems of coordination may arise for all mental representations, our particular differential utility account—which draws from philosophy of science for inspiration—could be especially appropriate as an explanation for the coexistence of mental representations that take the form of theories.

The answers to these questions about coexistence (among others) are obtainable with the methods reviewed here (e.g., priming tasks, inference tasks, speeded-reasoning tasks), but they may not be uniform across domains. Just as there is no one story of conceptual change that covers all domains, there may be no one story of explanatory coexistence that covers all domains. In some domains, we may maintain multiple theories because we need to match models of different complexity to problems demanding different levels of precision (e.g., quantitative vs. qualitative predictions of molecular diffusion; Chi, 2005), whereas in other domains, we may maintain multiple theories because we need to be able to engage in multiple discourses (e.g., formal vs. informal discussions of heat; Wiser & Amin, 2001).

IMPLICATIONS OF EXPLANATORY COEXISTENCE

Regardless of which account of explanatory coexistence is most accurate, the phenomenon of explanatory coexistence itself has important implications for our understanding of conceptual development and conceptual change. First, holding multiple theories of the same domain should be viewed as the rule, not the exception. Researchers who have uncovered evidence of explanatory coexistence in a single domain have previously explained that finding in terms of a single inductive bias—for example, an animacy bias in our understanding of living things (Goldberg & Thompson-Schill, 2009) or a teleological bias in our understanding of nature (Kelemen et al., 2013). The evidence to date, however, suggests that explanatory coexistence is true of many concepts in many domains (Shtulman & Harrington, 2016; Shtulman & Valcarcel, 2012), which, in turn, suggests that explanatory coexistence may be better understood as a symptom of heterogeneous cognitive demands in a complex world, and not as the consequence of several independent biases.

Second, a hallmark of intuitive theories is their causal-explanatory coherence (Shtulman, 2006; Vosniadou, 1994). It is this causal-explanatory structure that separates them from other forms of knowledge representation, such as schemas, scripts, or semantic memory. The finding that intuitive theories survive the acquisition of a scientific alternative suggests that, for individuals who have begun to learn the principles of a new scientific theory, the coherence of their inferences may be determined largely by context, with some contexts reliably eliciting scientific inferences and others reliably eliciting nonscientific inferences. Researchers interested in characterizing the content and structure of intuitive theories may thus be best served by studying genuine novices, or learners whose exposure to the scientific alternative is as minimal as possible. Studying older or more educated participants will likely yield inconsistent responding, especially if judgments are solicited under heterogeneous conditions. While inconsistent responses have often been viewed as evidence of fragmented beliefs (e.g., diSessa, 1993), such responses could also be evidence of competing theories—theories that are themselves internally coherent but, collectively, yield different inferences in different contexts. Inconsistent responses should thus be interpreted with caution, particularly when those responses are from individuals who have been “contaminated” by education. Likewise, demonstrating the coherence of naïve beliefs should be recognized as an empirical challenge, one that requires the right set of participants and the right set of tasks.

Third, coordinating two (or more) qualitatively distinct theories likely places demands on domain-general resources, including working memory, comprehension monitoring, and inhibitory control—resources traditionally classified as *executive function*. To date, little is known about the role that executive function plays in either the construction of scientific theories or the coordination of scientific theories with their nonscientific counterparts. One explanation for why Alzheimer's patients endorse nonscientific conceptions of life (Zaitchik & Solomon, 2008) and function (Lombrozo et al., 2007) to a substantially greater degree than age-matched controls is that Alzheimer's patients have deficits in executive functioning. Those deficits could interact with domain knowledge such that the salient perceptual features of a domain—for example, the animate aspects of living things or the functional aspects of natural kinds—capture Alzheimer's patients' attention and divert it away from features that play a more central role on a scientific construal of the domain.

Some preliminary support for this hypothesis is the finding that executive function may be a prerequisite to constructing a scientific theory of life in the first place (Zaitchik, Iqbal, & Carey, 2014). That is, elementary school–aged children who score high on measures of executive function demonstrate significantly more accurate conceptions of life, death, and bodily functions than do other children, even after controlling for age and verbal IQ. Likewise, preschool-aged children who score high on measures of executive function demonstrate significantly more accurate conceptions of mental states—deception, perceptual illusions, false beliefs—than do other children, even after controlling for age, gender, verbal IQ, motor ability, and family size (Carlson & Moses, 2001). These findings suggest that domain-general cognitive resources interact with domain-specific conceptual representations in ways that are relevant to the phenomenon of explanatory coexistence, but that remain largely unexplored.

Fourth, educators who aim to foster conceptual change in their students may need to do more than help them appreciate the logic of an ontologically distinct theory, an onerous task in and of itself (Chi, 2005; Ohlsson, 2009). They may also need to help students differentiate inferences that arise from a scientific theory from those that arise from a nonscientific competitor and to know when to apply each. For example, when students hear of a genetic similarity between two distantly related species—say, mice and humans—they may be inclined to interpret the similarity as evidence of an ancestral relation (mice as the ancestors of humans) rather than as evidence of a homologous trait. Likewise, when students hear of a disease outbreak in a foreign country, they may be inclined to interpret the outbreak as a form of divine retribution rather than as an epidemiological consequence of the local ecology. Given the prospect of such competing explanations, educators may need to introduce scientific theories not only as bodies of knowledge but also as methods of reasoning, stressing the difference between laypeople's intuitive approaches to a problem and the kinds of approaches adopted by a domain expert. Domain-specific scientific reasoning may be a developmental achievement, but it is also a resource-demanding skill that needs to be refined and practiced across the lifespan.

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