This paper has been accepted for publication in *Science & Education*. The final publication is available at http://link.springer.com/.

From ends to causes (and back again) by metaphor: the paradox of natural selection

Stefaan Blancke[1,*], Tammy Schellens[2], Ronald Soetaert[2], Hilde Van Keer[2] & Johan Braeckman[1]

[1]Research Unit The Moral Brain, Department of Philosophy and Moral Sciences, Ghent University, Sint-Pietersnieuwstraat 49, B-9000 Ghent, Belgium

[2] Department of Educational Studies, Ghent University, Henri Dunantlaan 2, 9000 Ghent.

[*]Corresponding author: st.blancke@gmail.be, tel.: ++32(0)9/264.79.17.

Abstract

Natural selection is one of the most famous metaphors in the history of science. Charles Darwin used the metaphor and the underlying analogy to frame his ideas about evolution and its main driving mechanism into a full-fledged theory. Because the metaphor turned out to be such a powerful epistemic tool, Darwin naturally assumed that he could also employ it as an educational tool to inform his contemporaries about his findings. Moreover, by using the metaphor Darwin was able to bring his theory in accordance with both the dominant philosophy of science in his time and the respected tradition of natural theology. However, as he introduced his theory of evolution by natural selection in *On the origin of species* in 1859, the metaphor also turned out to have a serious downside. Because of its intentional overtones, his contemporaries systematically misunderstood his metaphor not as a natural mechanism causing evolution to occur but as an agent who works towards particular ends. The difference in success between natural selection as an epistemic tool and its failure as an educational tool is labelled as a paradox. We explain the paradox from a cognitive perspective and discuss the implications for teaching evolution.

Keywords

Charles Darwin – metaphor – natural selection – evolutionary theory – biological education – history of biology – conceptual change

1. Introduction

Natural selection is one of the most famous metaphors in the history of science. In developing his theory of evolution by purely naturalistic mechanisms, Charles Darwin analogized the biological process of species change with artificial selection and in doing so named the process "natural selection". He subsequently employed the metaphor in his seminal work *On the Origin of Species* (1859). As a result, natural selection became inextricably tied to evolutionary theory, a link that persists until today. Because of its importance in the history of biology, the origin and usage of the metaphor has been the subject of numerous historical

studies. Darwin scholars have thereby discerned and discussed several benefits the metaphor of natural selection provided to Darwin in the course of developing and explaining his theory to his contemporaries. However, there is a significant discrepancy in the way the metaphor helped Darwin to shape his theory and the way Darwin's contemporaries systematically misunderstood natural selection as an intentional agent. This is the paradox of natural selection. We submit that this paradox can be explained by a cognitive approach by which natural selection can be both a very powerful epistemic tool but also a misleading educational tool. We conclude by discussing the implications of our approach for the teaching of evolutionary theory.

2. The selection of natural selection[1]

2.1. The wedge metaphor

Darwin's notebooks provide historians of science with valuable clues as to how to reconstruct Darwin's path of discovery towards the theory of evolution by natural selection. They show, for instance, that in the summer of 1837, Darwin first visualized his theory of common descent as a tree of life (B36).[2] However, it was a year later that he found the mechanism that was responsible for the formation of that tree. A crucial moment in this process was his reading of Thomas Malthus' *An essay on the principle of population* (1798) in September 1838, which made him reflect on the effects of different factors on the population size of species, such as predators and famine. He compared these effects with the workings of a hundred thousand wedges. In a now famous passage, dated 28 September, he wrote:

> The final cause of all this wedging, must be to sort out proper structure, & adapt it to changes. — to do that for form, which Malthus shows is the final effect (by means however of volition) of this populousness on the energy of man. One may say there is a force like a hundred thousand wedges trying force ~~into~~ every kind of adapted structure into the gaps ~~of~~ in the oeconomy of nature, or rather forming gaps by thrusting out weaker ones. (D135e)

This remarkable passage shows that, from the very beginning, Darwin tried to make sense of his emerging theory with the help of metaphorical language. At that time, however, Darwin considered artificial selection and the workings of nature to be entirely different in character for a host of reasons; thus, the metaphor of natural selection was not available to him. Most

[1] As natural selection is considered Darwin's most important contribution to science and philosophy, the origin of the concept has been the focus of extensive research and intense debate. Owing to Darwin's fortunate habit of trusting his thoughts on the emerging transmutation theory to little notebooks, historians can broadly reconstruct the process by which Darwin arrived at this mechanism. These records provide a timeline of Darwin's progress, helping us understand when Darwin formulated the mechanism as analogous to artificial selection, eventually giving rise to its name. As details of this process have been discussed elsewhere, there is no need to reiterate them here. Instead, we will rely on these analyses of this development and concentrate on some relevant passages and tendencies that might bear on the topic of this article. Highly informative in this regard are the works of Hodge and Kohn (1985), Millman and Smith (1997), Reif (2006) and Hodge (2009).

[2] For those readers who are unfamiliar with how Darwin's notebooks are referenced, the letter B refers to notebook B (which is the first of four notebooks on the transmutation of species). The adjoined number refers to the page of the notebook. All notebooks can be consulted online at http://darwin-online.org.uk.

importantly, Darwin was still convinced that, in nature, individuals became adapted to the circumstances affecting their development. On the other hand, in the process of artificial selection, features were developed that were not attuned to a particular environment, but to the breeder's fancy. Hence, these latter features were generally considered monstrosities. From a modern perspective, it would be tempting to conclude that Darwin was on the wrong track and to dismiss the wedge metaphor as a dead end. However, as the first attempt to help his mind "grapple with [the] great effect produced" by "the multiplication of little means" (C75, see above), the wedge metaphor, "this first fragile conception of natural selection" (Millman and Smith 1997, p. 170), certainly helped Darwin on the way of developing his theory. Soon thereafter, however, Darwin realized that artificial selection provided a more promising alternative.[3]

2.2. Artificial selection

Much of the ongoing debate pertains to the question of whether or not artificial selection played a major role in the discovery of natural selection itself. Did Darwin immediately frame his theory in terms of artificial selection or did he arrive at the analogy only after he had already grasped the core of his theory? Although Darwin himself promoted the first account in his *Autobiography*, on meticulously reading his notebooks, scholars have dismissed this version (Millman and Smith 1997; Herbert 1971; M. J. S. Hodge and Kohn 1985). Darwin still had trouble reconciling artificial selection with the works of nature when he penned down the first, fragile formulation of his germinating theory by the end of September 1838 in the image of wedges. As Ruse (1975) and others (L. T. Evans 1984; Herbert 1971) suggest, Darwin by then probably did appreciate the potential of artificial selection as a promising route to an evolutionary mechanism; however, at that point, the dissimilarities still outweighed the similarities. It would appear that, in the following months, Darwin increasingly realized that the dissimilarities might not be that significant after all. Two steps in particular were crucial in arriving at the analogy with artificial selection. First, Darwin had to accept that varieties in nature could be the product of mere chance, a fact he already acknowledged with respect to domestic variation. Second, he had to realize that varieties in artificially bred populations were adaptations to the breeder's picking. Having incorporated this into his thinking, Darwin could then infer that variations in nature were likewise picked, or selected, by the environment (M. J. S. Hodge and Kohn 1985; Millman and Smith 1997). By March 1839, Darwin had indeed taken both steps, producing a more mature version of his theory. Only then did he have "a theory by which to work" (Darwin 1958, p. 120), although it was far from finished (Largent 2009).

Whether or not Malthus appealed to Darwin's "earlier presentiments" on artificial selection (Richards 2009, p. 52), is perhaps of lesser importance to our purposes here. What is more interesting is that Darwin did not explicitly formulate his first attempts in the language of artificial selection. First came the image of wedges, which was only later replaced with an image of domestic breeding (however, see Reif 2006). Now, one could argue that Darwin replaced wedges with selection simply because the analogy with artificial selection offered

[3] For a cognitive approach to the wedge simile, see De Cruz and De Smedt (2010).

better mapping possibilities. In essence, artificial selection was more appropriate, for it has more features in common with natural selection than wedges do. This reply sounds reasonable, but it does not sufficiently explain why Darwin chose the analogy with artificial selection, rather than some other metaphor. Obviously, the similarities between artificial and natural selection do exist; still, at least two elements complicate such a straightforward account. One is that Darwin's contemporaries considered the works of nature to be completely alien to the process of selection under domestication. Most tellingly, Wallace, the co-discoverer of natural selection, never ceased to question and object to the way Darwin aligned their causal mechanism with the intentional act of breeding (Young 1971). In his seminal paper, *On the tendency of varieties to depart indefinitely from the original type*, Wallace wrote that "the two are so much opposed to each other in every circumstance of their existence, that what applies to the one, is almost sure not to apply to the other" (Darwin and Wallace 1858, p. 61). In fact, this view was so prevalent back then that Darwin's very discovery of the analogy was "a bold and original step" (L. T. Evans 1984, p. 138) to take. Second, Darwin himself only came to appreciate the similarities between artificial and natural selection through a slow and gradual process (L. T. Evans 1984; J. Hodge 2009; M. J. S. Hodge and Kohn 1985; Millman and Smith 1997). Both these elements suggest that the comparison between artificial and natural selection was not obvious; other factors too shaped Darwin's preference for natural selection. Indeed, Darwin scholars have pointed out several advantages of the metaphor of natural selection that go beyond the mere points of analogy with artificial selection.

3. The benefits of natural selection

3.1. Philosophy of science

One advantage of the metaphor of natural selection is that it allowed Darwin—or, at least, so he thought—to conform his theory to the philosophy of science of that period (Campbell 1986, 2003; Young 1971). Scientists were supposed to establish the *vera causa*, the true cause of a phenomenon, by strictly applying the scientific method, which was primarily based on induction. This 19th century devotion to the inductive method was brought on by the success of Newtonian physics. The use of hypotheses (in the sense of educated or informed guesses) was still highly suspect and restricted. Therefore, Darwin intended to demonstrate the independent existence (one character of a *vera causa*) of natural selection, by relating it to a commonly known process, artificial selection. When Darwin published his theory in the *Origin* twenty years later, he was confident that he had worked according to the prescriptions of the then reigning philosophy of science. Darwin was convinced he had proceeded in the realm of biology as Newton had done before him in the realm of physics. However, much to his own surprise, Darwin soon found out that many contemporary authors objected particularly strongly to his methods of inquiry. Even the philosophers of science, whom Darwin held in such high esteem, played down the scientific status of his work (Hull 2009). Ironically, both the Victorian philosophers of science and Darwin adhered to a method that was in fact less inductive that they made it out to be (Hull 2009; Ayala 2009).Whether Darwin did indeed follow the required procedures, or simply accommodated to them in his publications, is a topic for an entirely different discussion, one we do not have to engage in

here. It suffices to conclude that Darwin at least complied with the scientific standards of his time, and that, in his opinion, the analogy with artificial selection would suffice.

Evans (1984) hints at another advantage, which is somewhat connected to the previous point. He attributes critical importance to the analogy with artificial selection, claiming that "domesticated organisms not only provided the central analogue for his species theory, but played a key role in shaping the other concepts [a mechanism of change, sexual selection, force of inheritance] he needed to build that theory" (p. 136). Yet, keeping in mind the difficulties the analogy raised among Darwin's contemporaries, Evans feels the need to explain why Darwin never gave up on it. He suggests that the analogy offered Darwin the unique opportunity of testing his theory against the huge quantity of data gathered by plant and animal breeders. It helped him lift his theory from pure speculation to a well-supported factual claim. Thus, again, the analogy plays a crucial role in supporting the scientific character of Darwin's theory.

3.2. Natural theology

Other Darwin scholars noted that the analogy with artificial selection not only allowed Darwin to accommodate his theory to the then prevailing Baconian, inductive tradition within the philosophy of science. It also allowed him to frame his theory in accordance with yet another, respected tradition within British thought, that of natural theology. Natural theology rested (and, within some variants of creationism, still rests) primarily on a particular form of the design argument, namely the idea that the existence of God can be directly inferred from complex biological traits that occur abundantly in nature. The best known author supporting this tradition is William Paley,[4] who in his *Natural theology* (1802) had compared the human eye with a mechanic watch and had argued that, just like the functional complexity of the watch requires a watchmaker, the complexity of the eye requires an eye maker, viz. God. Concomitant to this idea was the conception of species as immutable products of God's work. This line of thinking about nature was still dominant among naturalists in the 1830s, including Darwin, who had read and admired Paley during his Divinity studies at Cambridge. Darwin was still highly supportive of the natural theological tradition when he embarked on his journey with the Beagle in 1831. Only after he had become a "transmutationist" a couple of months after his return to England in October 1836, and had developed a suitable natural explanation for biological adaptations between September 1838 and March 1839, he no longer needed to invoke an interventionist designer. Darwin, of course, realized that his theory parted with natural theology, which was still the reigning paradigm among most of his contemporaries (McCalla 2006). Nevertheless, by employing the term "natural selection", Darwin was able to connect his new theory to some elements of the older tradition, thereby smoothing the transition.

[4] In fact, Paley stood as one of the last in a long line of natural theologians. He relied heavily on the works of his predecessors (e.g., Bernard Nieuwentyt, William Derham, John Ray), copying their arguments and most of their examples.

However, Darwin scholars who have touched upon the concord of the theory of natural selection with the tradition of natural theology seem to differ in opinion on the extent to which Darwin appealed to the then prevailing modes of thought. Therefore, they explain this benefit of natural selection, whereby it resonates with basic concepts within the tradition of natural theology, rather differently. Campbell (1986, p. 361), for instance, argues that Darwin only assumed the then prevailing "grammar of culture", thus "outflank[ing] natural theology by associating its conventional terms with his new evolutionary meanings". For example, in the *Origin*, Darwin regularly uses the term "contrivance", which in natural theological literature points to a contriver. Darwin's contriver, however, was not God, but rather natural selection. By expressing his radically new theory in a language his contemporaries were familiar with and accepted, Darwin tried to win his audience over to this novel way of thinking about nature. In this sense, the metaphor of natural selection purely functioned as a rhetorical device (see also Moore 1997). As Depew (2009, p. 251) notes "the *Origin* paints natural selection's scrutiny as sublimely oriented toward the good of each being in order to enlist the assumed affective and argumentative dispositions of its audience" However, other scholars deny that Darwin so purposefully covered his "wolf" theory in sheep's clothing. Today, Darwin's theory of natural selection is rightly considered a landmark of modern thought, but Darwin himself of course did not have any knowledge of the future developments based on his theory. Nonetheless, Darwin realized that his theory was groundbreaking—after all, in 1844 he did describe it in a letter to Hooker as the confession of a murder—but he was also a man of his time. This means that, at least for some period after he arrived at his theory of evolution by natural selection, Darwin did not distance himself from, or broke with, certain conceptions of nature that were common back then, but which we nowadays consider irreconcilable with evolutionary theory. Ospovat (1980, 1981), for instance, concedes that Darwin introduced the concept of chance in thinking about nature by suggesting that the variation upon which natural selection worked occurred randomly and thus did away with the specific natural theological ideas on design. Yet, according to Ospovat, he did not immediately abandon the idea of perfect adaptation, as he replaced it with relative adaptation some fifteen years later. In addition, even in the *Origin* he still held on to a notion of design, in which the designer worked through secondary, natural laws rather than by direct interaction. Thus, he still adhered to a general teleology:

> The element of chance in natural selection meant that there could be no detailed plan, in which even man's idea of God would be a necessary outcome of nature's laws (man himself is not a necessary outcome of the working of natural selection). But Darwin still believed nature was programmed to achieve certain general ends. We might say that he believed in a general, though not special teleology. [...] Only later did Darwin come to doubt even this sort of design in nature." (Ospovat 1980, pp. 193-194)

According to Kohn (1989), Darwin is not simply another natural theologian, nor is he a downright materialist. Because of his background and his upbringing, both traditions left a distinct mark on his thinking; and Darwin is only able to combine them by means of the metaphor of natural selection because it allows him to secularize the message of natural theology. As Kohn (1989, p. 221) writes: "Darwin opens the door for a non-theological naturalism that yet retains a teleological ethos. This is a genuine secularization: it unslips the

scholastic knot of God and purpose by translating the self-evident Christian myth into the self-evident scientific myth of evolving function". Consequently, Darwin had come up with a "teleology without Purpose" (Kohn 1989, p. 234), a solution foreshadowed by thinkers such as Jean Baptiste Lamarck and Robert Chambers (Bowler 2009) and still held as a justifiable position by some current scholars (e.g., Nagel 2012).

Richards (2009) claims that Darwin regarded evolution as progressing towards the production of higher animals and especially humans. Within this teleological framework, Darwin pictured natural selection as a benevolent, moral and intelligent agent that worked towards those ends. As such, Darwin soft-pedaled the horrifying message of the Malthusian struggle for life. Interestingly, Richards asserts that Darwin not simply presented natural selection as an intelligent being to help his readers cope with the cruel aspects of his theory, but that Darwin himself thought of natural selection as exactly such an agent:

> The model Darwin had chosen to explain *to himself* the process of selection in nature was that of a powerfully intelligent being, one that had foresight and that selected animals to produce beautiful and intricate structures. [...] Nature, the analog of this being, was thus conceived not as a machine but a supremely intelligent force. (Richards 2009, p. 58, our italics)

Consequently, describing natural selection as an intelligent and moral being involved much more than Darwin formally accommodating to the language of his time. It actually helped in shaping much of his theorizing on how species change and adaptations arise. Moreover, it also played a key role in the way Darwin communicated his theory, and thus how it was received. From the start, Darwin had been concerned about how to explain his theory to his contemporaries. In Notebook E (E118), on 12 March 1839, he writes:

> Varieties are made in two ways — local varieties, when whole mass of species are subjected to same influence, & this would take place from changing country: but greyhound, race-horse & poulter Pidgeon have not been thus produced, but by training, & crossing & keeping breed pure — & so in plants effectually the offspring are picked & not allowed to cross. — Has nature any process analogous — if so she can produce great ends — But how — even if placed on Isl[d] if &c &c — make the difficulty apparent by cross-questioning — Here give my theory. — excellently true theory.

This passage illustrates that, almost from the very beginning, Darwin intended to explain his theory to others in the same manner as he had explained it to himself. Young (1971, p. 455) agrees that Darwin's anthropomorphic treatment of natural selection had far-reaching consequences, as he notes, "In moving from artificial to natural, Darwin retains the anthropomorphic conception of selection, with its voluntarist overtones. Thus the analogy is not merely a reflection of the process of discovery. The terms in which it is expressed had important consequences for the nature and the reception of the theory". It seems that personification, and even deification, of nature and natural selection was not only intended to help an unprepared Victorian audience deal with a radically new vision on nature, one that departed radically from the older tradition of natural theology. It also made Darwin think of his theory in a more familiar way.

To sum up, the metaphor of natural selection had many advantages. It allowed Darwin to attune his theory to the then prevailing philosophy of science and offered him unique opportunities to test his ideas against the data and experience of breeders. However, natural selection offered an advantage that the wedge metaphor could not, for it allowed him to think of the evolutionary process of random variation, environmental selection and hereditary accumulation as the actions of an intelligent being.[5] As such, it not only helped Darwin's audience to overcome its resistance against an explanation that was essentially blind and uncaring, it also allowed Darwin to develop his theory to a level that would have not been available to him if he had stuck to a purely mechanical metaphor.

4. The paradox of natural selection

Despite its promising instructional qualities, to many of Darwin's contemporaries, the metaphor proved to be terribly misleading. They systematically interpreted the metaphor literally and considered natural selection a selecting agent (see also, Browne 2002, p. 59). The discord grew to the point that, on 2 July 1866, Alfred Russel Wallace, the co-discoverer of natural selection, complained in a letter to Darwin that many people failed to grasp the "self acting & necessary effects" of natural selection, which they consistently interpreted as the acting of a selector, an "intelligent chooser".

> Now I think this arises almost entirely from your choice of the term "Nat. Selection" & so constantly comparing it in its effects, to Man's selection, and also to your so frequently personifying Nature as "selecting" as "preferring" as "seeking only the good of the species" &c. &c. To the few, this is as clear as daylight, & beautifully suggestive, but to many it is evidently a stumbling block.

According to Wallace, the metaphor impeded rather than furthered people's acceptance of the purely natural explanation he and Darwin had found to account for the origin of species and their adaptive features. Indeed, in the *Origin,* Darwin relied heavily on intentional language when discussing natural selection. For instance, on page 84, he wrote:

> It may be said that natural selection is daily and hourly scrutinising, throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good; silently and insensibly working, whenever and wherever opportunity offers, at the improvement of each organic being in relation to its organic and inorganic conditions of life.

In order to avoid potential misunderstanding of the expression "so necessary and self evident a principle" in terms of the intentions and actions of a personified Nature, Wallace suggested to Darwin to replace "natural selection" with the phrase "survival of the fittest", the term coined by Herbert Spencer. In his response letter, written three days later, Darwin politely declined Wallace's proposal, as he trusted that, "[a]s in time the term must grow intelligible, the objections to its use will grow weaker and weaker." He doubted "whether the use of any term would have made the subject intelligible to some minds, clear as it is to others." Darwin also explained his reasons behind the decision to retain the metaphor of natural selection.

[5] Interestingly, for these reasons, creationists will accept natural selection but reject common descent (E. M. Evans et al. 2010).

First, in his view, it highlighted the analogy with artificial selection, which he thought of as "a great advantage"; moreover, in matters of style, natural selection could be "used as a substantive governing a verb," which was not the case with "survival of the fittest." Finally, and rather practically, natural selection was by then so prevalent that it was simply too late to discard it. Elsewhere (1861, p. 85), he wrote:

> It has been said that I speak of natural selection as an active power or Deity; but who objects to an author speaking of the attraction of gravity as ruling the movements of the planets? Everyone knows what is meant and is implied by such metaphorical expressions; and they are almost necessary for brevity. So again, it is difficult to avoid personifying the word Nature; but I mean by Nature, only the aggregate action and product of many natural laws, and by laws the sequence of events as ascertained by us. With a little familiarity, such superficial objections will be forgotten.

Darwin's confidence in the benefits of the metaphor of natural selection stands in sharp contrast to the systematic failure of his contemporaries to grasp his theory correctly. We submit that this paradox can be explained from a cognitive perspective. Such a perspective also creates the opportunity to apply our findings concerning this particular episode in the history of science to the science education.

5. A cognitive account

In order to develop a cognitive perspective, one can rely on recent findings from developmental and cognitive psychology, anthropology and the educational sciences to shed new light on the usage and appreciation of the metaphor of natural selection by Darwin and his contemporaries. One of the main outputs of cognitive science is the image of the human mind holding intuitive ontologies about relevant aspects in its surroundings (Boyer and Barrett 2005). That is, the mind does not simply register and consider the world as it is, but shapes its experiences and understanding of the world according to a number of early-developing and implicit expectations about how the world functions. For instance, even at an early age, young infants expect objects to behave according to a number of principles (Spelke 1990). Similarly, at a later age, children also develop intuitive notions about the living world, including psychological essentialism, teleological thinking and the intentional stance.

Psychological essentialism purports the view that organisms hold an unobservable and immutable essence that determines their identity and development. Our minds carve up nature into categories, the members of which share an inner essence that further remains unspecified ("a placeholder essence"). These mental categories typically have rich inferential structures, so that the mind does not have to learn everything anew and can make trustworthy predictions about an organism's development and behavior. Even five-year-olds think of animals as having an unobservable 'inside' that procures and maintains category identity, acts as an inherent cause, and provides them with an innate potential that cannot be overruled by the environment (for a review, see Gelman 2004).

Similarly, studies on teleological thinking have repeatedly demonstrated that young children intuitively understand the world in teleological terms. Moreover, subjects indiscriminately

ascribe purposes not only to artifacts, but also to both living and non-living things and their properties. Rocks are pointy because "animals wouldn't sit on them and smash them" or "animals […] could scratch on them when they got itchy" (Kelemen 1999b, p. 1443); a lion is for "to go in the zoo" or "to look at" (Kelemen 1999a, p. 251). Although the original experiments were only conducted with American children, similar findings pertaining to British children who live in a less religious environment suggest that children do not derive this "promiscuous teleology" from their particular culture (Kelemen and Di Yanni 2005; however see, Diesendruck and Haber 2009). Instead, it is more likely that the preference for teleological explanations is due to mental dispositions that constrain children's understanding of the natural world (Kelemen 2003; Kelemen and Di Yanni 2005). Adults tend to be more selective in their teleological reasoning, and are more prone to accept purely physical explanations for the natural world phenomena. However, when questioned under time pressure, adults too seem to revert to a teleological way of thinking (Kelemen and Rosset 2009). This finding suggests that, through education, the teleological stance is suppressed rather than replaced by scientifically sound explanations. The view that our teleological intuitions act as a default setting of our mind to deal with the natural world is confirmed by experiments with scientifically uneducated adults (Casler and Kelemen 2008) and Alzheimer patients (Lombrozo et al. 2007).

The human mind is not only inclined to view the world in terms of purposes, but also tends to interpret natural events and phenomena as intentional acts. This intentional stance (Dennett 1987), or theory of mind, which allows one to understand and explain other people's behavior in terms of their mental states (desires, beliefs, intentions, feelings, etc.), evolved in response to the requirements set by social living. It considerably facilitates one's interactions with others if one assumes that their actions are motivated by a mind that functions similarly to one's own mind. However, owing to evolutionary reasons, the intentional stance is easily triggered, thus leading people to attribute intentions to phenomena and events in which no agents are involved. Agentive reasoning comes very easily to the mind—we insult our car when it suddenly "refuses" to drive any further and we damn our computer for failing to execute our orders properly. Likewise, our hyperactive theory of mind makes us highly susceptible to explanations of the biological world in terms of intentional acts.

Each of these predispositions interferes with a scientific understanding of the biological world (Sinatra et al. 2008), but their impact is not necessarily pejorative and needs to be qualified (E. M. Evans et al. 2012). Gelman and Rhodes (2012), for instance, identify five distinct ways in which psychological essentialism hampers people's understanding of evolutionary theory. First, it leads to the assumption that biological categories are stable and immutable, that whereas it also makes one underestimate within-category variability (see also Shtulman and Schulz 2008; Shtulman and Calabi 2012; Shtulman 2006). However, Gelman and Rhodes (2012, p. 15) also acknowledge that essentialism may reflect biological reality, but only if "one means that there are discoverable classifications in nature that are non-arbitrary and deeply revealing of non-obvious properties, then this view is compatible with the position of many biologists and philosophers" (p. 15). Similarly, Coley and Muratore (2012) argue that folk biological concepts impede with people's understanding of variability within a

population and common descent,—two basic concepts within evolutionary theory. Nevertheless, they point out that "the pervasive tendency to perceive folk generic groupings as the basic elements of biological reality means that we intuitively grasp the same elemental components of the biological world as those acknowledged by science" (2012, p. 42). Likewise, teleological thinking leads people to misconstrue natural selection as a goal-directed process. They wrongly assume that adaptations occur in immediate response to an organism's need or consider evolution to tend towards a particular goal (Kelemen 2012; Kampourakis and Zogza 2007). However, understanding that organisms can change in response to their environment out of a need to survive may provide a useful scaffold in the development of a scientific understanding of natural selection (Legare et al. 2013; E. M. Evans et al. 2012; Spiegel et al. 2012). Philosopher of biology Michael Ruse (2003) has argued that a teleological understanding of adaptive traits is highly appropriate as it captures important aspects of evolutionary biology. Intentional explanations for the origins of species possibly indicate that children are receptive to the idea that species did not always exist (E. M. Evans et al. 2012, p. 187). Moreover, students integrate or synthesize contradictory concepts in diverse ways, sometimes resulting in synthetic blends that can function as a stepstepping-stone towards a more scientific understanding (E. M. Evans 2001; Mortimer 1995; Legare et al. 2012; Vosniadou et al. 2008). Thus, the way in which information will be processed and interpreted greatly depends on how education engages with students' cognitive predispositions. When left unattended or inappropriately addressed, they can result in severe adult resistance to scientific ideas (Bloom and Weisberg 2007). Intentional or agentive reasoning, and language in particular, appears to have a detrimental effect on students' understanding of evolutionary processes (Moore et al. 2002). A recent study revealed that desired-based explanations, in contrast with need-based explanations, negatively affects children's apprehension of biological change (Legare et al. 2013).

Cognitive predispositions generally give rise to particular biases that incline the mind to prefer accounts of the world that align closely with its intuitive understanding (Sperber 1996; Blancke and De Smedt 2013; E. M. Evans 2001). As to the mind's essentialism, teleological thinking and its intentional stance, these particular predispositions help to explain the abundance of creationist stories throughout history and across the globe. In Western culture, they lead people to readily endorse the creationist story in the book of Genesis in various manners and to quickly accept an explanation of biological functional complexity (adaptations) in terms of intelligent design, the main position defended in the tradition of natural theology. Importantly, because these biases arise due to the universal cognitive architecture of the human mind, Darwin himself was predisposed to embracing such accounts himself. He indeed admitted that, when he left England on HMS the Beagle, he was still a creationist impressed by the works of the natural theologian William Paley. Living in a culture that enforced his teleological and intentional intuitions, Darwin at that point had no reason whatsoever to revise his beliefs.

His outlook changed, however, when, as a result of his journey, Darwin became increasingly confronted with data that contradicted and thus made him question his creationist convictions. They induced Darwin to set out for a different explanation, not in terms of intentional design,

but in terms of natural causes. However, even for a mind as ingenious as Darwin's, this transition from ends to causes did not come easily and required the introduction of specific epistemic tools. One was the first drawing of an evolutionary tree on page 37 of Notebook B, which helped him to grasp the notion of common descent. Another was the metaphor of natural selection and its analogy with artificial selection, by which he could make sense and further explore the natural process by which evolution occurred.

Metaphors, which Burke (1969, p. 503) describes as "a device for seeing something in terms of something else", pervade our everyday language (Lakoff and Johnson 1980). In the representational view, metaphors are not simply linguistic devices, but rather conceptual tools that effectively shape our thinking, particularly in more abstract domains (Lakoff 1993; Schön 1993). In science, as Kuhn (1979, p. 416) puts it, they "play an essential role in establishing a link between scientific language and the world". Nonetheless, they also provide scientists with new perspectives by which they can expand or improve their understanding of the world. In particular, analogies and metaphors are invoked to facilitate reasoning within and about an unfamiliar domain, for they allow one to mentally transfer the inferential structure of a familiar domain unto the unfamiliar one. According to Brown (2003, p. 17), "[t]his, in brief, is what metaphor is all about: applying information and understanding from one domain of experience, which we call the source domain, to enhance understanding of another domain, called the target domain, that is typically more abstract". In the case of natural selection, Darwin applied his knowledge of artificial selection to reason about the natural process he had discovered. Moreover, the metaphor did not only allow him to map the relevant aspects of artificial selection unto natural selection, it simultaneously allowed him to continue to reason about and within a very contra-intuitive mental construct in intuitively appealing intentional terms.

In the process of developing his theory, Darwin needed to discard some of the elements that belonged to the source domain, which were inapplicable to the natural processes of evolution. From this perspective, it is entirely reasonable that he struggled with accepting relative instead of perfect adaptation or, just like today's students, adhered to a synthetic blend by which he no longer viewed evolution as an intentional, but a teleological process nonetheless. Overall, however, the metaphor proved to be an exceptionable epistemic tool that enabled Darwin's mind to accomplish a conceptual change in which his folk biological notions were suppressed to allow for a counterintuitive scientific understanding of the living world. Unsurprisingly, as the metaphor had worked so well for him as a conceptual tool, Darwin assumed that natural selection would also make an excellent educational tool by which he could explain his theory to his contemporaries. However, the intuitive appeal of the metaphor soon proved too strong. Instead of overriding people's intuitions, natural selection enforced their understanding of the biological world in terms of intentional acts. Instead of learning to think about the breeders' preferences as a constituent of a species natural environment, people instead considered nature to be some kind of agent. Living in a cultural environment that favored such an interpretation, their minds easily resisted the conceptual change Darwin had hoped to realize.

Hence, the paradox of natural selection—the tension between the importance of the metaphor in the development of Darwin's thinking and the systematic misunderstanding of the metaphor by Darwin's contemporaries—makes perfect sense from a cognitive perspective. To a mind that is intuitively inclined to reason about nature in intentional terms, a metaphor relying on such terms offers an excellent tool for overcoming persistent biases when developing counterintuitive non-intentional models of the biological world. Because of the cognitive ease by which such an intuitively appealing metaphor is processed, the mind is nonetheless readily seduced into taking its intentional overtones literally.

6. Implications for science education

Although one should be careful about straightforwardly connecting episodes from within the history of science with the individual development of students in science education (Kampourakis and Zogza 2007), the cognitive perspective developed above certainly allows for a number of conclusions pertaining to the teaching of evolutionary theory. Evolutionary theory is notoriously difficult to learn and understand and students are liable to a number of typical errors (Bishop and Anderson 1990; Nehm and Reilly 2007; e.g., Alters and Nelson 2002; for a review, see Gregory 2009b). As noted above, many of these errors arise because of cognitive constraints that systematically interfere with people's understanding of biological evolution (Rosengren et al. 2012; see also Thagard and Findlay 2010). Among these errors is the idea that natural selection can be interpreted as a natural selector, which clearly resonates with the way in which Darwin's contemporaries misrepresented the metaphor (Gregory 2009b). If the metaphor of natural selection, because of its intentional overtones, is partly responsible for the persistent misapprehensions in Darwin's time, it can also mislead students today. However, fully grasping the basics of evolutionary theory requires conceptual change and, as we pointed out above, metaphors provide excellent tools for accomplishing this goal. If natural selection allowed Darwin to realize conceptual change in his own mind, this at least provides us with good reason to assume that modern teachers can use the metaphor and the analogy as an educational tool as well.

In general, the story of the metaphor of natural selection, with its ambiguity, its paradox, and its reputation in science education, tells a universal story of the human mind that evolved in response to particular adaptive problems, not to do science. As a result, it continuously struggles to acquire a more objective understanding of how the world functions (De Cruz et al. 2011; Blancke and De Smedt 2013). In this sense, it is ironic that natural selection, among other evolutionary processes, ultimately produced a mind that systematically misunderstands this important, but highly counterintuitive evolutionary mechanism. Furthermore, the *metaphor* of natural selection also leads people to misconstrue the mechanism There is little that one can do about the evolutionary reason for the systematic confusions about natural selection, but what about the metaphorical one? Should we try to replace natural selection, in particular as an analogy with artificial selection, with another metaphor? Wallace suggested to Darwin to use "survival of the fittest"—a term coined by Herbert Spencer. However, the term might be highly popular as a cultural idiom, but it denotes all kinds of struggles, not necessarily Darwinian ones. Later, Darwin did regularly add "survival of the fittest" as a synonym, but never as a replacement.

The paradox of natural selection teaches an important lesson about the use of metaphorical and analogical language in science communication and education in general. Educational and cognitive scientists repeatedly point out that teachers must be careful about the language they employ in the classrooms (e.g., Moore et al. 2002; Sinatra et al. 2008). "Watch your metaphors!", warned Burke (1984, p. 274). In the case of biological education, it is, for instance, very tempting to use teleological language as a shortcut to explain how and why adaptations evolved (eyes for seeing, wings for flying, and so on). Given students' predispositions for assigning purpose to the living world phenomena, however, such terminology might have dramatic effects on their understanding of the causal evolutionary processes that are involved in shaping adaptations (González Galli and Meinardi 2011). Moreover, comparing the complexity of adaptations with the design of human artifacts guides people into assuming that biological functions are the product of intentional design as well (Pigliucci and Boudry 2011). Similarly, although the analogy with artificial selection certainly provides us with some very good insights about biological evolution (Gregory 2009a; Dawkins 2009), teachers should use the analogy and the metaphor that refers to it in a careful manner. As Wall (2009, p. 76) puts it, they need to "master the art of metaphor (whilst recognising the inherent dangers that accompany this)". Several studies show that the theory can be taught relatively successfully by means of interventions that do not rely on the metaphor (e.g., Kampourakis and Zogza 2009). Even five-year-olds can be taught basic aspects of evolution by employing pictures that are specifically designed to avoid triggering the children's teleological intuitions (Kelemen 2012). Dismissing the metaphor of natural selection altogether, however, might be too drastic a solution. The fact that the metaphor of natural selection allowed Darwin to transgress his biased biological understanding to arrive at a more accurate understanding indicates its exceptional potential of realizing conceptual change, at least to a certain extent. It would be a dreadful waste if teachers did not tap into this potential by using the metaphor and the underlying analogy as an educational tool. Hence, educators, popular science writers, and even scientists themselves can continue to use it, while being aware of the metaphor's pitfalls and explicitly inform their students and audiences about them.

Practically, because intentional language in particular causes students to misrepresent basic aspects of biological evolution (Legare et al. 2013; Moore et al. 2002), teachers might opt to avoid employing natural selection as an intentional agent or as a subject in sentences as much as possible. In other words, they might prefer not to use it the way Darwin did in *On the origin of species*, because such linguistic shortcuts could indeed be very misleading to students' minds. In addition, teachers can explain to their students that the metaphor is only legitimate in regards to some, but not all, properties the natural process of evolution shares with artificial selection. To be more specific, random variation occurs in both natural and artificial selection, but only the second scenario includes a selective agent. However, Darwin's intellectual development shows that, once undone from its intentional overtones, the metaphor might actually help students to attain at least a teleological understanding of evolution, which then, in turn, can function as a scaffold to construe a more scientific understanding. If teachers use the metaphor to that purpose, and explicitly and adequately confront students with inaccurate teleological notions, natural selection may remain a

powerful educational tool. Further research is, however, needed to examine and fine-tune the precise impact of our cognitive approach employing the metaphor in the teaching of evolutionary theory. Nonetheless, our cognitively informed account shows that the metaphor of natural selection, and the historical discussions it has inspired, clearly provides a good opportunity to teach evolutionary biology in a historical, philosophical, and sociological context..

References

Alters, B. J., & Nelson, C. E. (2002). Perspective: Teaching evolution in higher education. *Evolution, 56*(10), 1891-1901.

Ayala, F. J. (2009). Darwin and the scientific method. *Proceedings of the National Academy of Sciences of the United States of America, 106*(Supplement 1), 10033-10039, doi:10.1073/pnas.0901404106.

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching, 27*(5), 415-427.

Blancke, S., & De Smedt, J. (2013). Evolved to be irrational? Evolutionary and cognitive foundations of pseudosciences. In M. Pigliucci, & M. Boudry (Eds.), *The philosophy of pseudoscience* (pp. 361-379). Chicago: The University of Chicago Press.

Bloom, P., & Weisberg, D. S. (2007). Childhood origins of adult resistance to science. *Science, 316*(5827), 996-997, doi:10.1126/science.1133398.

Bowler, P. J. (2009). Darwin's originality. *Science, 323*(5911), 223-226, doi:10.1126/science.1160332.

Boyer, P., & Barrett, H. C. (2005). Domain specificity and intuitive ontology. In D. M. Buss (Ed.), *The handbook of evolutionary psychology* (pp. 96-118). Hoboken: John Wiley & Sons.

Brown, T. L. (2003). *Making truth: Metaphor in science*. Urbana : University of Illinois Press.

Browne, J. (2002). *Charles Darwin. The power of place* (Vol. 2). London: Pimlico.

Burke, K. (1969). *A grammar of motives* (2nd ed.). Los Angeles: University of California Press.

Burke, K. (1984). *Attitudes toward history* (3rd ed.). Los Angeles: University of California Press.

Campbell, J. A. (1986). Scientific revolution and the grammar of culture: The case of Darwin's *Origin*. *Quarterly Journal of Speech, 72*(4), 351-376.

Campbell, J. A. (2003). Why was Darwin believed? Darwin's origin and the problem of intellectual revolution. *Configurations, 11*(2), 203-237.

Casler, K., & Kelemen, D. (2008). Developmental continuity in teleo-functional explanation: Reasoning about nature among Romanian Romani adults. *Journal of Cognition and Development, 9*(3), 340-362, doi:10.1080/15248370802248556.

Coley, J. D., & Muratore, T. M. (2012). Tree, fish, and other fictions. Folk biological thought and its implications for understanding evolutionary biology. In K. S. Rosengren, S. K. Brem, E. M. Evans, & G. M. Sinatra (Eds.), *Evolution challenges. Integrating research and practice in teaching and learning about evolution* (pp. 22-46). New York: Oxford University Press.

Darwin, C. (1837-1838). *Notebook B [transmutation of species]* http://darwin-online.org.uk/content/frameset?viewtype=side&itemID=CUL-DAR121.-&pageseq=1.

Darwin, C. (1838a). *Notebook C [transmutation of species]*: http://darwin-online.org.uk/content/frameset?viewtype=side&itemID=CUL-DAR122.-&pageseq=1.
Darwin, C. (1838b). *Notebook D [transmutation of species]*: http://darwin-online.org.uk/content/frameset?viewtype=side&itemID=CUL-DAR123.-&pageseq=1.
Darwin, C. (1838-1839). *Notebook E [transmutation of species]*: http://darwin-online.org.uk/content/frameset?viewtype=side&itemID=CUL-DAR124.-&pageseq=1.
Darwin, C. (1859). *On the origin of species by means of natural selection : Or the preservation of favoured races in the struggle for life*. London: John Murray.
Darwin, C. (1861). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life* (3d ed.). London: John Murray.
Darwin, C. (1958). *The autobiography of Charles Darwin and selected letters*. New York: Dover.
Darwin, C., & Wallace, A. R. (1858). On the tendency of species to form varieties, and on the perpetuation of varieties and species by natural means of selection. *Journal of the Proceedings of the Linnean Society of London, Zoology, 3*, 45-62.
Dawkins, R. (2009). *The greatest show on earth. The evidence for evolution*. London: Bantam.
De Cruz, H., Boudry, M., De Smedt, J., & Blancke, S. (2011). Evolutionary approaches to epistemic justification. *Dialectica, 65*(4), 517-535, doi:10.1111/j.1746-8361.2011.01283.x.
De Cruz, H., & De Smedt, J. (2010). Science as structured imagination. *Journal of Creative Behavior, 44*(1), 29-44.
Dennett, D. C. (1987). *The intentional stance*. Cambridge: MIT Press.
Depew, D. J. (2009). The rhetoric of the *origin of species*. In M. Ruse, & R. J. Richards (Eds.), *The cambridge companion to the "Origin of species"* (pp. 237-255). New York: Cambridge University Press.
Diesendruck, G., & Haber, L. (2009). God's categories: The effect of religiosity on children's teleological and essentialist beliefs about categories. *Cognition, 110*(1), 100-114, doi:10.1016/j.cognition.2008.11.001.
Evans, E. M. (2001). Cognitive and contextual factors in the emergence of diverse belief systems: Creation versus evolution. *Cognitive Psychology, 42*(3), 217-266, doi:10.1006/cogp.2001.0749.
Evans, E. M., Rosengren, K. S., Lane, J. D., & Price, K. L. S. (2012). Encountering counterintuitive ideas. Constructing developmental learning progression for evolution understanding. In K. S. Rosengren, S. K. Brem, E. M. Evans, & G. M. Sinatra (Eds.), *Evolution challenges. Integrating research and practice in teaching and learning about evolution* (pp. 174-199). New York: Oxford University Press.
Evans, E. M., Spiegel, A. N., Gram, W., Frazier, B. N., Tare, M., Thompson, S., et al. (2010). A conceptual guide to natural history museum visitors' understanding of evolution. *Journal of Research in Science Teaching, 47*(3), 326-353, doi:10.1002/tea.20337.
Evans, L. T. (1984). Darwin's use of the analogy between artificial and natural selection. *Journal of the History of Biology, 17*(1), 113-140.
Gelman, S. A. (2004). Psychological essentialism in children. *Trends in Cognitive Sciences, 8*(9), 404-409, doi:10.1016/j.tics.2004.07.001.
Gelman, S. A., & Rhodes, M. (2012). "Two-thousand years of stasis": How psychological essentialism impedes evolutionary understanding. In K. S. Rosengren, S. K. Brem, M. E. Evans, & G. M. Sinatra (Eds.), *Evolution challenges. Integrating research and practice in teaching and learning about evolution* (pp. 3-21). New York: Oxford University Press.

González Galli, L., & Meinardi, E. (2011). The role of teleological thinking in learning the Darwinian model of evolution. *Evolution: Education and Outreach, 4*(1), 145-152, doi:10.1007/s12052-010-0272-7.

Gregory, T. R. (2009a). Artificial selection and domestication: Modern lessons from Darwin's enduring analogy. *Evolution: Education and Outreach, 2*(1), 5-27, doi:10.1007/s12052-008-0114-z.

Gregory, T. R. (2009b). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach, 2*(2), 156-175.

Herbert, S. (1971). Darwin, Malthus, and selection. *Journal of the History of Biology, 4*(1), 209-217.

Hodge, J. (2009). The notebook programmes and projects of Darwin's London years. In J. Hodge, & G. Radick (Eds.), *The Cambridge companion to Darwin. Second edition* (pp. 44-72). Cambridge: Cambridge University Press.

Hodge, M. J. S., & Kohn, D. (1985). The immediate origins of natural selection. In D. Kohn (Ed.), *The Darwinian heritage* (pp. 185-206). New Jersey: Princeton University Press.

Hull, D. L. (2009). Darwin's science and victorian philosophy of science. In J. Hodge, & G. Radick (Eds.), *The Cambridge companion to Darwin. Second edition.* (pp. 173-196). Cambridge, UK: Cambridge University Press.

Kampourakis, K., & Zogza, V. (2007). Students' preconceptions about evolution: How accurate is the characterization as "Lamarckian" When considering the history of evolutionary thought? *Science & Education, 16*(3-5), 393-422, doi:10.1007/s11191-006-9019-9.

Kampourakis, K., & Zogza, V. (2009). Preliminary evolutionary explanations: A basic framework for conceptual change and explanatory coherence in evolution. *Science & Education, 18*(10), 1313-1340, doi:10.1007/s11191-008-9171-5.

Kelemen, D. (1999a). The scope of teleological thinking in preschool children. *Cognition, 70*(3), 241-272.

Kelemen, D. (1999b). Why are rocks pointy? Children's preference for teleological explanations of the natural world. *Developmental Psychology, 35*(6), 1440-1452.

Kelemen, D. (2003). British and American children's preferences for teleo-functional explanations of the natural world. *Cognition, 88*(2), 201-221, doi:10.1016/s0010-0277(03)00024-6.

Kelemen, D. (2012). Teleological minds. How natural intuitions about agency and purpose influence learning about evolution. In K. S. Rosengren, & E. M. Evans (Eds.), *Evolution challenges: Integtrating research and practice in teaching and learning about evolutionary theory* (pp. 66-92). Oxford: Oxford University Press.

Kelemen, D., & Di Yanni, C. (2005). Intuitions about origins: Purpose and intelligent design in children's reasoning about nature. *Journal of Cognition and Development, 6*(1), 3-31.

Kelemen, D., & Rosset, E. (2009). The human function compunction: Teleological explanation in adults. *Cognition, 111*(1), 138-143, doi:10.1016/j.cognition.2009.01.001.

Kohn, D. (1989). Darwin's ambiguity: The secularization of biological meaning. *British Journal for the History of Science, 22*(73), 215-239.

Kuhn, T. S. (1979). Metaphor in science. In A. Ortony (Ed.), *Metaphor and thought* (pp. 409-419). Cambridge: Cambridge University Press.

Lakoff, G. (1993). The contemporary theory of metaphor. In A. Ortony (Ed.), *Metaphor and thought* (pp. 202-251). Cambridge: Cambridge University Press.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.

Largent, M. A. (2009). Darwin's analogy between artificial and natural selection in the *Origin of species* In M. Ruse, & R. J. Richards (Eds.), *The Cambridge companion to the "Origin of species"* (pp. 14-29). New York: Cambridge University Press.

Legare, C. H., Evans, E. M., Rosengren, K. S., & Harris, P. L. (2012). The coexistence of natural and supernatural explanations across cultures and development. *Child Development, 83*(3), 779-793, doi:10.1111/j.1467-8624.2012.01743.x.

Legare, C. H., Lane, J. D., & Evans, E. M. (2013). Anthropomorphizing science: How does it affect the development of evolutionary concepts? *Merrill-Palmer Quarterly-Journal of Developmental Psychology, 59*(2), 168-197.

Lombrozo, T., Kelemen, D., & Zaitchik, D. (2007). Inferring design - evidence of a preference for teleological explanations in patients with Alzheimer's disease. *Psychological Science, 18*(11), 999-1006.

McCalla, A. (2006). *The creationist debate. The encounter between the bible and the historical world*. London: T & T Clark International.

Millman, A. B., & Smith, C. L. (1997). Darwin's use of analogical reasoning in theory construction. *Metaphor and Symbol, 12*(3), 159-187.

Moore, R. (1997). The persuasive Mr. Darwin. *Bioscience, 47*(2), 107-114.

Moore, R., Mitchell, G., Bally, R., Inglis, M., Day, J., & Jacobs, D. (2002). Undergraduates' understanding of evolution: Ascriptions of agency as a problem for student learning. *Journal of Biological Education, 36*(2), 65-71.

Mortimer, E. (1995). Conceptual change or conceptual profile change? *Science & Education, 4*(3), 267-285, doi:10.1007/bf00486624.

Nagel, T. (2012). *Mind and cosmos. Why the materialist neo-Darwinian conception of nature is almost certainly false*. Oxford: Oxford University Press.

Nehm, R. H., & Reilly, L. (2007). Biology majors' knowledge and misconceptions of natural selection. *Bioscience, 57*(3), 263-272, doi:10.1641/b570311.

Ospovat, D. (1980). God and natural selection: The Darwinian idea of design. *Journal of the History of Biology, 13*(2), 169-194.

Ospovat, D. (1981). *The development of Darwin's theory : Natural history, natural theology, and natural selection, 1838-1859*. Cambridge: Cambridge University Press.

Paley, W. (1802). *Natural theology: Or, evidence of the existence and attributes of the deity*. London.

Pigliucci, M., & Boudry, M. (2011). Why machine-information metaphors are bad for science and science education. *Science & Education, 20*(5-6), 453-471, doi:10.1007/s11191-010-9267-6.

Reif, W. E. (2006). Darwin on picking, sorting, separating, isolating, etc.: The development of his theory of natural selection. *Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen, 240*(2), 153-205.

Richards, R. J. (2009). Darwin's theory of natural selection and its moral purpose. In M. Ruse, & R. J. Richards (Eds.), *The Cambridge companion to the "Origin of species"* (pp. 47-66). New York: Cambridge University Press.

Rosengren, K. S., Brem, S. K., Evans, E. M., & Sinatra, G. M. (2012). *Evolution challenges. Integrating research and practice in teaching and learning about evolution*. New York: Oxford University Press.

Ruse, M. (1975). Charles Darwin and artificial selection. *Journal of the History of Ideas, 36*(2), 339-350.

Ruse, M. (2003). *Darwin and design. Does evolution have a purpose?* Cambridge: Harvard University Press.

Schön, D. A. (1993). Generative metaphor: A perspective on problem-setting in social policy. In A. Ortony (Ed.), *Metaphor and thought* (pp. 137-163). Cambridge: Cambridge University Press.
Shtulman, A. (2006). Qualitative differences between naive and scientific theories of evolution. *Cognitive Psychology, 52*(2), 170-194, doi:10.1016/j.cogpsych.2005.10.001.
Shtulman, A., & Calabi, P. (2012). Cognitive constraints on the understanding and acceptance of evolution. In K. S. Rosengren, S. K. Brem, E. M. Evans, & G. M. Sinatra (Eds.), *Evolution challenges. Integrating research and practice in teaching and learning about evolution* (pp. 47-65). New York: Oxford University Press.
Shtulman, A., & Schulz, L. (2008). The relation between essentialist beliefs and evolutionary reasoning. *Cognitive Science, 32*(6), 1049-1062, doi:10.1080/03640210801897864.
Sinatra, G. M., Brem, S., & Evans, M. E. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach, 1*(2), 189-195, doi:10.1007/s12052-008-0037-8.
Spelke, E. S. (1990). Principles of object perception. *Cognitive Science, 14*(1), 29-56, doi:10.1207/s15516709cog1401_3.
Sperber, D. (1996). *Explaining culture. A naturalistic approach*. Oxford: Blackwell.
Spiegel, A., Evans, E. M., Frazier, B., Hazel, A., Tare, M., Gram, W., et al. (2012). Changing museum visitors' conceptions of evolution. *Evolution: Education and Outreach, 5*(1), 43-61, doi:10.1007/s12052-012-0399-9.
Thagard, P., & Findlay, S. (2010). Getting to Darwin: Obstacles to accepting evolution by natural selection. *Science & Education, 19*(6), 625-636, doi:10.1007/s11191-009-9204-8.
Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3-34). New York: Routledge.
Wall, A. (2009). *Myth, metaphor and science*. Chester: Chester Academic Press.
Young, R. M. (1971). Darwin's metaphor: Does nature select? *Monist, 55*(3), 442-503.