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# Ignorance, misconceptions and critical thinking

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## Abstract:

In this paper we investigate ignorance in relation to our capacity to justify our beliefs. To achieve this aim we specifically address scientific misconceptions, i.e. beliefs that are considered to be false in light of accepted scientific knowledge. The hypothesis we put forward is that misconceptions are not isolated false beliefs, but rather form part of a system of inferences – an explanation – which does not match current scientific theory. We further argue that, because misconceptions are embedded in a system, they cannot be rectified simply by replacing false beliefs with true ones. To address our misconceptions, we must rather act on the system of beliefs that supports them. In the first step of our analysis, we distinguish between misconceptions that are easy to dispel because they represent simple errors that occur against the background of a correct explanatory apparatus and misconceptions that are, on the contrary, very difficult to dispel because they are the product of pseudo explanations. We show that, in the latter case, misconceptions constitute an integral part of an incorrect explanation and the reasons that support such misconceptions are deeply misleading. In the second step, we discuss various approaches that have been adopted to address the problem of misconceptions. Challenging the notion that directly addressing and criticizing specific misconceptions is an effective approach, we propose that critical thinking is the most fruitful means to deal with misconceptions. We define the core competences and knowledge relevant for the practice of critical thinking and discuss how they help us avoid misconceptions that arise from accepting beliefs that form part of a mistaken explanation.

Keywords: ignorance, misconceptions, critical thinking, evidence, argument, beliefs

## 1. Introduction

Let's consider the case in which you believe that *there is a cat in your neighbor's garden*. If we ask you why you believe this, you might answer that you have seen it. Granted that you know what 'cat', 'neighbor' and 'garden' mean, you can justify your belief merely on the basis of this observation. And yet, only a small number of the beliefs you hold can be justified in this way. For example, you might believe that *an apple a day keeps the doctor away* or even that *the European economic situation is not going to improve in the next decade*. Beliefs such as these do not depend directly on observations but are based on other beliefs that support them.

The reason why we believe that *an apple a day keeps the doctor away* might be that apples are fruits, that fruits contain vitamins and that consuming a certain amount of vitamins is healthy, even though excessive consumption of fruit might be dangerous, because it is unhealthy to ingest too much sugar, and fruits also contain sugar; thus, an apple a day (no more, no less) is ideal for an individual's daily needs. Since following a proper diet is key for good health, and since we need medical attention when we are not in good health, a proper diet – part of which is an apple a day – should keep the doctor away. All of these beliefs about sugar, vitamins, a proper diet, health, doctors, etc. describe the reasons for believing that an apple a day keeps the doctor away; they justify our belief from the point of view of our belief system. Similar but more complex reasoning applies to the belief that *the European economic situation is not going to improve in the next decade*: this is based on a number of other beliefs related to how we think economic growth can be realized, how we assess European policy in this respect and the course of events we expect to unfold in the next few years.

If a person has both good reasons to believe and evidence for something, their belief is more likely to be true. On the contrary, if a belief a person holds is not based on good reasons and evidence, it is more likely to be false. However, this is not always the case. It is also possible that a person holds a false belief for good reasons or holds a true belief for the wrong reasons. Suppose that you suddenly wake up while you are sleeping in your bed and have no idea what time it is. You left the blinds open, but the room is dark. The clock on the nightstand reads 1:08. Since the clock was working properly when you went to bed and it is still completely dark, you are justified in believing that *it is 1:08 am*. And yet, in fact, your clock stopped working during the night and your partner closed the blinds when s/he came to bed; the correct time is actually *6:21* in the morning. In this case you hold a false belief in spite of the fact that you had good reasons to hold it. The opposite can also happen. We might correctly believe, for example, that *Einstein was a genius*, but the reason why we do so might be that we believe that he is the person who created the original recipe for linguine with clam sauce. In fact, we might think that the original recipe for linguine with clam sauce is exceptional; that only a genius can have created something that exceptional; that Einstein created it; and that, therefore, Einstein is a genius. In this case, our belief is true (Einstein is indeed a genius!), but the reasons we have for holding this belief are wrong.

This last example is particularly relevant in considering the form of ignorance we discuss in this work which does not concern our beliefs *per se*, but *the reasons we have for holding them*. Indeed, the philosophical tradition considers ignorance mostly in terms of a lack or absence of knowledge (Smithson 1989): a person should be considered ignorant if s/he has false beliefs or if s/he disbelieves something that is true. However, this tradition has also defined knowledge in terms of true *justified* beliefs, linking the issue of knowledge to that of justification. In light of this tradition, people should not only be considered ignorant when their beliefs are false but also when they have no good reasons to justify them – in which case, the belief about Einstein's genius would be a genuine case of ignorance. The truth value of our beliefs and the reasons we have to

support them are two factors that play an equal role in determining whether such beliefs should be considered knowledge. Of course, we cannot expect that the justification a person can provide for a belief s/he holds is complete or perfect; indeed, it will always be partial, and its adequacy can be measured in degrees according to how well or badly s/he understands the subject matter.[1]

To investigate ignorance from this point of view is not only interesting from a theoretical perspective, but also relevant in terms of figuring out a way to remedy ignorance. Indeed, it is clear from the picture we just sketched that, since most of our beliefs rely on other beliefs for justification, if we want to add a new belief to our belief system, we must introduce or adjust other beliefs such that the system will support it (someone will come to believe that *the European economic situation is not going to improve in the next decade* only if s/he accepts the reasons we give him/her for why this is the case). Similarly, to modify a belief we already have, we must act on others in the system so that they support the new belief instead of the old one (our belief that *the European economic situation is not going to improve in the next decade* – be it true or false – cannot be modified unless we alter the reasons we have to hold it).

In order to address ignorance from this angle, we will concentrate on so-called *misconceptions*. Misconceptions are "ideas that are at a variance with accepted views" (Fisher 1983), i.e. they are beliefs that diverge from the ones generally accepted by a community or a group of experts or scientists (Stein, Larrabee and Barman 2008). More precisely, as Sanger and Greenbowe have clarified, the word "misconception" refers to "conceptual and propositional knowledge that is inconsistent with or different from the commonly accepted scientific consensus and is unable to adequately explain observable scientific phenomena" (Sanger and Greenbowe 1997, p. 378). This point is important for our investigation of ignorance here for several reasons. First of all, directing our attention to misconceptions allows us to take a pragmatic stance and avoid a number of epistemological issues concerning the notion of knowledge involved in our analysis (realist vs. deflationary) as well as the idea of justification underlying our study. Indeed, we will assume that we should consider as true/false the beliefs that comply/do not comply with the positions generally accepted by the scientific community at the present time and that we can consider the explanations provided by these scientific theories as a yardstick for determining whether individuals' justifications for their beliefs are more

[1] In the literature, the approach to ignorance that considers the possession of true justified beliefs as a necessary condition for having knowledge and, by contrast, the absence of one of these conditions as sufficient to establish ignorance is called the *Standard View of Ignorance* (Le Morvan 2011, 2012, 2013, Le Morvan and Peels 2016). Recently, epistemological research has developed a new approach called the *New View of Ignorance* in which the role assigned to justification and to the capacity to explicitly offer reasons in support of our beliefs has been weakened and in which a person is considered to be ignorant primarily in the case in which s/he holds false beliefs. (On the so-called *New View* see Peels 2010, 2011, 2012; Le Morvan and Peels 2016). On the one hand, the *New View* denies – contrary to what we suggest – that justification plays a central function in determining whether we are or are not ignorant about some topic. However, on the other hand, it takes a step towards our approach: it not only places stronger emphasis on the cognizing powers of the subject than the "standard view" but also considers the possibility of distinguishing between various degrees of ignorance. In fact, by discussing the impossibility of providing a complete justification for a belief, it makes it possible to consider ignorance as a continuum rather than in a categorical manner, distinguishing between various degrees in which a person can be said to be ignorant as for the reasons s/he has to hold his/her beliefs (for a conception of ignorance as an epistemic status that comes in degrees and ignorance as the incapacity to adequately and completely answer questions concerning our beliefs cf. Nottelman 2016). Of course, we cannot expect that people are able to provide a complete justification for their beliefs and even the issue of what an acceptable justification should look like is controversial. However, especially when considering beliefs concerning (relatively simple) phenomena that have a widely accepted scientific explanation, we can take a practical stance and assume that scientific theories which are commonly accepted by the scientific community at a given time provide us a measure for which beliefs should be considered to be true or false at that time and what a justification of them would ideally look like. On this basis, we can also assess (or approximate) the distance between scientific knowledge and individual beliefs as well as the distance between the way scientific theories justify specific pieces of knowledge and the way in which people justify their beliefs about the same phenomena.

or less adequate. Secondly, what is considered to be a misconception changes over time and depends on the development of our scientific knowledge. That the sun goes around the earth is today considered a scientific misconception, but was once an unanimously held scientific position, firmly grounded in the perception that the terrain beneath our feet does not move. As scientific conceptions evolve, misconceptions change accordingly, and what was once a scientific view can become a misconception. An analysis of misconceptions makes it clear that both knowledge and its converse – ignorance – are dynamic notions: that, once again, they depend on inferential relationships and that knowledge of these inferences is essential for the mastery of individual pieces of knowledge. Thirdly, the class of misconceptions includes a number of variegated beliefs concerning issues that go from the very simple to the very complex. Their analysis and an examination of their differences can help us understand the reasons why people hold various kinds of false or ungrounded beliefs. Finally, misconceptions are widely investigated in the literature and we can reflect on them while drawing on a number of studies already available that have considered various strategies to dispel misconceptions and their consequences.

In this paper, we will investigate misconceptions in relation to the reasons people have to endorse or to reject them. In the first step, we will distinguish between misconceptions that are easy to dispel because they represent mere errors that occur against the background of a correct explanatory apparatus and misconceptions that are, on the contrary, very difficult to counter because they are the product of pseudo explanations. We will show that, in the latter case, misconceptions constitute an integral part of the incorrect explanation and this makes the reasons a person has to support them deeply misleading. In the second step of the analysis, we will discuss various approaches that have been adopted to address the problem of misconceptions. We will challenge the idea that an approach aimed at directly addressing and criticizing specific misconceptions is indeed effective and argue for a different line of action. We will show that the most fruitful means to deal with misconceptions are those offered by the practice of critical thinking. We will define the core competences and knowledge that are needed for critical thinking and discuss why these are needed to avoid the ignorance that results from accepting pieces of knowledge that are not coherent with a reasonable explanation.

## 2. Misconceptions and their degrees of severity

Beliefs such as “Tiny specks of matter don’t weigh anything” (di Sessa 2006, 93), “A girl can get pregnant from oral sex” (Wynn, Foster and Trussell 2009), “Most people only use 10% of their brains”, “People with severe mental illness are prone to violence” (Bensley and Lilienfeld 2015), or “Autism has become an epidemic” (Taylor and Kowalski 2012) are usually defined as *misconceptions*, i.e. “beliefs that are held contrary to known evidence” (Taylor and Kowalski 2004, 15). The idea of *misconception* derives from that of *conception* which indicates “the sum of a person's ideas and beliefs concerning something” (Conception, n.d.). Just as a *conception* can be described as a “view”, i.e. the set of a person’s ideas concerning something, a *misconception* does not only describe an individual false belief, but a set or collection of false beliefs a person holds about something. Typically, misconceptions concern beliefs that are considered to be false in the light of our accepted, current scientific knowledge. In fact, most studies on this phenomenon speak of *scientific misconceptions*. The literature on this topic frequently focusses on scientific misconceptions that are widespread in the population of non-experts (indeed, specific tests to identify and evaluate well-known scientific misconception in various fields have been developed in the literature, for an example, cf. Gardner and Brown 2013). However, false beliefs about scientifically proven and broadly accepted phenomena fall under the definition of misconception, regardless of the number of people who hold them.

Misconceptions are an extensively studied phenomenon (Gilbert and Watts 2008). They are widely shared not only by the general population but also by students (Bensley, Lilienfeld and Powell 2014; Bensley and Lilienfeld 2015) and even by experts (see, *inter alia*, Smith, di Sessa and Roschelle 1994; Kikas 2004). Students exhibiting misconceptions are often capable of solving quantitative examination problems concerning the subject matters involving their false beliefs but at a theoretical level they still lack an "understanding of the underlying concepts" (Sanger and Greenbowe 1997, 377). Research on misconceptions has shown that misconceptions are very resistant to change (Herron, 1990; Stein, Larrabee and Barman 2008, Goris and Dyrenfurth 2010) and that a scientific education only slightly reduces levels of inaccuracy. Indeed, students (i.e. people with some knowledge of such matters) perform only marginally better than the general public on misconception tests (Taylor and Kowalski 2004; Kowalski and Taylor 2009; Taylor and Kowalsky 2014; Furnham and Hughes 2014; Bensley and Lilienfeld 2015). Misconceptions also have a negative impact on a person's comprehension of new information and interfere with the acquisition of new knowledge (Kendeou and van den Broek, 2005; Smith, di Sessa and Roschelle 1994). People who exhibit them are more prone to compartmentalize information and to contradict themselves or to offer inconsistent explanations (Garnett and Treagust 1992a, 1992b; Kendeou and van den Broek 2005). Moreover, students with misconceptions use different terminologies to describe the same phenomena and use everyday language instead of technical terms as well as superficial and vague descriptions to refer to scientific theories (Garnett and Treagust 1992a, 1992b).

Misconceptions are found across all fields of knowledge: there are no important differences in the nature and structure of misconceptions in different fields, such as physics (see, *inter alia*, Sanger and Greenbowe 1997; Potvin and Cyr 2017), medicine (see, *inter alia*, Pressman 2011), biology (see, *inter alia*, Gregory 2009), psychology (Firestein 2012, p. 25-28), etc. And yet they can be distinguished hierarchically on the basis of their degree of severity: *in spite of the fact that misconceptions are false beliefs and as false beliefs should be emended*, some are more *innocuous* than others because they can be more easily identified and dismissed.

Consider for example the following misconceptions: (1) 'Whales are fish'; (2) 'Kathmandu is the capital of Peru'; (3) 'Soymilk is milked from an animal called soy'. People who hold these beliefs could be quickly persuaded that they were false, if someone argued with them. A person might believe that whales are fish because they exhibit the same traits and live in the same habitats as fish. However, if one brings that person's attention to the differences between fish and mammals and their respective characteristics (cold-blooded vs. warm-blooded, strictly aquatic vs. breathes air, lays eggs vs. gives birth to live young and feeds babies milk from mammary glands), this belief would be immediately dispelled. In fact, to abandon this belief does not cause any great perturbation in the system of our beliefs: all we knew about fish, mammals and animals in general remains intact; the only change concerns the categorization of whales.

The same kind of reasoning applies to (2) and (3). We might have formed the belief that Kathmandu is the capital of Peru starting from some imprecise knowledge such as 'Kathmandu is the capital of some poor country' and 'Peru is a poor country'. Or we might have developed the belief that soymilk is milked from an animal called soy on the basis of our knowledge that 'Cow's milk is milked from cows', 'Sheep's milk is milked from sheep' and 'Goat's milk is milked from goats'. However, beliefs of this kind can be easily abandoned just by looking at a geographic map or by reading the label for soymilk. To reconsider beliefs like these we do not need to modify the system into which our beliefs has been organized: we can continue to believe that countries have capitals and that milk comes from animals. We only need to readjust some marginal information concerning Peru (whose capital is Lima), Kathmandu (which is the capital of Nepal), soy (which is a plant) and the word 'milk' (which is often improperly used to describe various vegetable beverages that vaguely resemble milk in terms of their color, flavor or nutritional properties).

If misconceptions such as those described in the previous examples are easily challenged and dismissed, the same does not apply to other kinds of beliefs that are much more *pernicious* since they are deeply rooted in an individual's belief system. Take, for example, beliefs on the existence of bad/good luck, karma, faith healing, or beliefs concerning the reliability of the horoscope, or the possibility of extrasensory perception, or more generally implying the existence of paranormal or of supernatural phenomena (for a description of these kinds of beliefs cf. e.g. Irwin 2009). People who believe in these things cannot be easily persuaded that they are false. The reason is that these beliefs form part of a consistent and interrelated system of thought: they are inherent to the way in which such people think about a number of phenomena.

Let's consider faith healing. Faith healing can hardly be conceived as an isolated belief, unrelated and inconsistent with the other beliefs a person holds.[2] Thus, to believe in faith healing one must hold a number of other beliefs that support it such as that supernatural phenomena are possible, that causality obtains outside the natural order; in particular, one must endorse a view in which spiritual entities exist and can play a causal role in healing processes (and possibly in getting sick).

These are quite general beliefs that affect explanations for a number of other phenomena. All of these beliefs form part of an inferential system that describes how an individual's belief system is organized, i.e. which specific commonsensical or naïve biological, psychological, physical theories a person endorses (Aarnio and Lindeman 2005; Lindeman and Aarnio 2007; Pennycook et al. 2012; Kirby 2018; Kukzmann 2017; Özmen 2004; Simpson and Marek 1988). These beliefs are so interconnected with each other in a broad explanation that they cannot be challenged individually; instead, the whole system of causal and ontological principles on which these beliefs rely must be discredited. In this particular case, the very idea that immaterial entities exist and can causally interact with the material world to influence biological phenomena and result in health or illness must be disqualified. For this reason, a belief in faith healing is generally a global and pervasive belief.

The difference in severity between erroneous beliefs such as faith healing on the one hand and 'Kathmandu is the capital of Peru' on the other can be traced back to two main interconnected factors. First of all, the belief that 'Kathmandu is the capital of Peru' is quite closely related to observation. If you believe that geographical maps are correct representations that depict the boundaries between countries, their capitals and so on, then you can observe that Kathmandu is not the capital of Peru by looking at a map. On the contrary, the belief in faith healing is more theoretical: you can (maybe) observe healing processes, but certainly not their causes. No matter what model of epistemic justification you choose, beliefs that are more influenced by observations can be changed without causing great perturbation to our belief system, while more theoretical beliefs (those less closely tied to observation, are at a higher level of hierarchy in the structure of our belief system, or more at the center of its web) can be modified only at the cost of readjusting a large number of other beliefs.[3]

[2] In fact, it is not impossible for an individual to hold a belief that is inconsistent with other beliefs s/he holds, and yet it would be irrational for him/her to do so. As Davidson argues: "Strictly speaking, then, the irrationality consists not in any particular belief but in inconsistency within a set of beliefs." (Davidson 1985/2004, p. 192) According to a widely shared view in psychology developed by Leon Festinger, inconsistencies cannot be psychologically accepted by the subject who will make every possible effort to rationalize and thus resolve them. In the same vein, Davidson (1982/2004; 1986/2004) points out how the inconsistencies we are sometimes victim of can be explained only by postulating a kind of compartmentalization of the mind. However, generally people seek internal congruency among their beliefs and coherence plays a pivotal role in the way we interpret human thinking (on this cf. also Thagard 2000).

[3] In epistemology, justification has been viewed in various ways. Justification might be conceived as being linear: in this case an individual belief is proven to be true by a set of other beliefs and those other beliefs are proven to be true by another set and so on, until we reach some beliefs that are based on experience and are therefore considered – if not

Highly theoretical beliefs determine the very principles according to which inferential relationships in the belief system are organized. They work like a world-view by giving us key principles to interpret the events we experience: they determine what ontology we accept, what kind of causal interactions we establish between the phenomena in our universe and thus also the explanatory structure of the inferences in the system, i.e. which inferences support which beliefs and why. To hold a belief such as faith healing, for example, a person must also embrace a number of related beliefs about physical and non-physical entities as well as the causal relationships that can occur within and between them. Thus, the belief in faith healing can only be critiqued together with the explanatory principles that justify it. Faith healing is a good example of a belief that can be disputed only on the condition that a large part of the belief system is called into question.

These considerations lead us to the second factor that makes the belief that 'Kathmandu is the capital of Peru' less pernicious than the belief in faith healing. In fact, a belief such as 'Kathmandu is the capital of Peru' is quite easy to dispel because it results from a line of reasoning which is globally correct and consistent with the way in which geography organizes and explains phenomena. This presupposes that territory is divided into countries, that each state has a capital, that capital cities are generally big, and so on. Furthermore, it is also based on the correct information that Kathmandu is a big city and even a capital city and that Peru is a state. The mistake is due 'only' to an incorrect association between two pieces of information: the modification of this association does not invalidate the geographic explanation it is based on. On the contrary, the belief in faith healing results from a line of reasoning that is globally incorrect in light of how medical science explains healing and even in light of how science in general explains causal relationships. Thus, the whole system of belief that revolves around it is erroneous when compared to the way in which science explains the phenomena.

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indisputable – at least well-grounded: as BonJour (1985, p. 26) formulates it, "sufficient by itself to satisfy the adequate justification condition for knowledge". Alternatively, justification can be viewed holistically as an interferential network of beliefs that are interconnected within a system and providing mutual support but are supported by experience only altogether as a whole. In this case, what justifies a belief is primarily its coherence with the system (this form of holism is commonly discussed in relation to Quine 1951; for a discussion of different justification models cf. Elgin 2005; van Cleve 2005). While strong forms of holism would consider a belief to be justified only if it is coherent with the whole system of beliefs that includes it, more moderate forms of holism support the view that justification depends on some chunks of this system. Typically, they also embrace some weak form of foundationalism in which some beliefs are considered more basic than others because they are closer to experience, i.e. observational, and thus serve as a foundation for others. (On moderate vs. strong holism from the point of view of Quine's philosophy and on Quine's later arguments in favor of a moderate form of holism cf. De Rosa and Lepore 2004). To numerous epistemologists, the idea that we can always apply linear models of justification that lead us to some fundamental beliefs appeared to be implausible in the light of the complexity of our system of knowledge. For this reason, they argued for a holist picture of knowledge in which beliefs are connected to each other within an inferential network and mutually sustain each other (cf. Quine and Ullian 1970; Bonjour 1985; Harman 1993; Thagard 2007). At the same time, the view that all the beliefs of a complex beliefs system are also involved in the justification of each appeared to be too extreme as well as problematic from an epistemological point of view. In fact, this implies that, when even one single belief in the system is changed, all others must be modified accordingly. This excessive interdependence of beliefs makes the system as a whole too instable (cf. Fodor and Lepore 1992, chap 2). For this reason, many epistemologists have considered a moderate form of holism as the most plausible option. And yet, independently of which view of the structure of knowledge we favor and thus of which is the specific model of justification we prefer, at least some principles of inferential justification can be considered to be shared by all these models. Indeed, independently of whether we think that our beliefs are structured "like a building that rests upon a foundation" or "like a web where the strength of any given area depends on the strength of the surrounding areas" (Steup 2018), we always presuppose that *beliefs form a congruent structure* and that *their relationships are somehow explanatory*. We will say something more on this last factor below, but – since we will consider scientific theory as a benchmark to assess misconceptions – we will mainly just assume that the inferential relationships presupposed by scientific theories are explanatory, i.e. that they are form part of an appropriate explanation.

To sum up, the suggestion implicit in the comparison of these examples is that some false beliefs are more innocuous than others because their revision requires only some local change of the system and is therefore easier to achieve. We have identified two factors that determine whether a change will be more local vs. global, i.e. superficial vs. pervasive. The first concerns the nature of the false belief at issue and in particular whether it is more or less directly linked to observation: in fact, modification of beliefs that are more directly linked to observation only requires a local change of the system, while the modification of theoretical beliefs requires a more pervasive modification. A second factor concerns the inferential relationships that support the false belief at issue: these might be (more or less) globally correct and consistent with the way in which science organizes and explains phenomena or they might be (more or less deeply) misleading with respect to it. The more the inferential relationships that support a belief are globally correct and consistent with the way in which science organizes and explains phenomena, the less pervasive the modification in the belief system required to emend it.

This second factor shifts our attention from the structure of our knowledge (i.e. from the idea that beliefs need different degrees of support depending on whether they are more or less directly linked to observation) to the reliability of the specific inferential relationships that form this structure, i.e. to the appropriateness of the explanations these relationships provide. Indeed, the principles of inferential justification that the sciences rely on do not consist in internal coherence only (otherwise a belief such as faith healing would also be scientific if supported by a system of congruent beliefs on spiritual entities and their causal relationships with the material world); the sciences further require that these inferences build an adequate explanation of phenomena.

This discussion allows us to say something more about the examples of misconceptions we mentioned at the beginning of this section and to discuss how they were derived, what they depend on, how we could emend them and how difficult this would be.

Let's start from the belief that 'A girl can get pregnant from oral sex'. According to the picture we suggested, this has been inferred from some sort of explanation concerning how reproduction occurs. A person might believe that a girl can get pregnant from oral sex because s/he holds a wrong theory of reproduction in which fertilization occurs when sperm (or, more generally, male bodily fluids) comes into contact with any part of a woman's body. This misconception derives from a wrong line of reasoning that does not identify the correct causal chain that leads to pregnancy. Of course, we can address this misconception on its own and tell this person that a girl does not get pregnant from oral sex. However, unless we globally emend the explanation this misconception is based on, the problem will not be truly solved. This person might, for example, still think that a girl can get pregnant when male bodily fluids come into contact with some other parts of the female body.

As long as we draw conclusions that rely on wrong inferences – on an erroneous explanation of phenomena – we will keep producing new false beliefs (i.e., new misconceptions) that are derived from these inferences. Thus, to radically emend this kind of misconception, we have to challenge the whole explanation of how reproduction works and replace it with a set of inferences that fits the explanation of reproduction currently offered by biology and medical science. When the previous set of inferences is replaced with a correct explanation of reproduction, all the misconceptions related to it will be solved at once without addressing them explicitly by virtue of the logical relations among them. How easy or difficult it will be to emend the set of inferences that support the idea that a girl can get pregnant from oral sex will depend on how close and compatible this original set is with the scientific explanation of fertilization.

Note that a person's misconception might also be more or less pervasive depending on the extent of his/her ignorance. Indeed, an incorrect explanation of reproduction might be accompanied by a more general lack

of medical and anatomical knowledge. In this case, its effects will be more global, since they will affect aspects of knowledge unelated to reproduction. And yet it is also possible that a person does not know how reproduction works but has contextual knowledge related to some other aspects of how the human body works: for example, s/he might correctly believe that it is much more dangerous to stab someone in the chest than in the leg because some organs are vital and are located in the chest. In this last case, the effects of the wrong explanation may be more local and concern only those aspects of the person's medical and anatomical knowledge related to fertilization.

Analogous observations apply to the other misconceptions we referred to previously. A belief such as 'Tiny specks of matter don't weigh anything' might depend on a naïve understanding of weight based on an analogy with the experience of lifting objects people have in their everyday life: if an object is very small, we do not need to exert any additional physical force to lift it when we raise our arm. A misconception like this might not be innocuous because it relies on inferences driven by our everyday experience which overlook how physical science explains things such as matter, mass and weight.

A belief such as "Most people only use 10% of their brains" might derive from an explanation presupposing that humanity has untapped potential and that the brain, like space (e.g. in computer memory), can somehow be used only partially. This misconception also appears quite difficult to dispel since it relies on an analogy that does not catch the actual inferential relationships identified by a neurobiological explanation of how the brain works.

A belief such as 'Autism has become an epidemic' might be inferred from a view in which autism is spreading through the world's population because it is contagious or because it results from something that is affecting more and more people worldwide. This misconception is due to the fact that people do not identify the correct relationships among the phenomena or the properties involved: they mistake the increasing number of diagnoses of autism with an increasing number of cases of autism, or they identify accidental correlations such as that between the increasing number of diagnoses of autism and the increasing number of children who receive a vaccine and mistake this for an actual regularity. On this basis, they develop false inferences such as 'Children who are getting the recommended vaccinations run a higher risk of being affected by autism'; 'Nowadays an increasing number of children are getting the recommended vaccinations'; thus, 'Nowadays an increasing number of children are affected by autism' and 'Autism has become an epidemic'.

Finally, a belief such as 'People with severe mental illness are prone to violence' might derive from the information that some violent outbursts are due to mental illnesses and this is overgeneralized leading people to think that – at least when mental illnesses are severe – they always lead to violent outbursts. This might also stem from a commonsensical view that people who suffer from mental illnesses are dangerous, criminal and uncontrollable.

All these misconceptions diverge quite deeply from the corresponding scientific theories. However, at least intuitively, they appear to be less severe than others: they appear to be, for example, easier to emend than beliefs related to faith healing, as discussed above. One could argue that the belief in faith healing is just more pervasive since it entails that embracing a larger number of other beliefs concerning material and immaterial phenomena as well as their relationships and thus relies on an explanation that diverges more widely from the explanation given by scientific theories. This is certainly all part of the problem. However, another aspect of the problem lies in a factor we have not considered yet: the belief in faith healing is based on an explanation that is difficult to prove wrong. In fact, whether a false belief is more or less innocuous vs. pernicious depends not only on how extensively we must intervene in the belief system to emend it or on how much the set of inferences that support it diverge from the explanation given by science, but also on

*how easy or difficult it is to challenge the set of inferences that supports it on the basis of further observations and reflections* (Posner, Strike, Hewson and Gertzog 1982).

As for this issue, a positive suggestion comes from Reichenbach (1951/1968, chap. 2) and from his analysis of the difference between good and bad explanations – which he calls pseudoexplanations – as well as from his discussion on the reasons why some pseudoexplanations are more difficult to dispel and thus more pernicious than others. In Reichenbach's view, explanations are essentially generalizations: to develop new knowledge means to discover correct generalizations and to show that "a certain implication holds for all things of a specified kind". "Generalization" – he adds – "is the very nature of explanation. What we mean by explaining an observed fact is incorporating that fact into a general law" (Reichenbach (1951/1968, p. 5)[4] In order to identify the correct generalization, we must distinguish between the properties that are relevant for the generalization and those that are not. To illustrate this issue, he discusses the example of fire: "That fire can be produced by rubbing wood in a certain way is a knowledge derived by generalization from individual experiences; the statement means that rubbing wood in this way will always produce fire. […] What is irrelevant, such as the particular shape or size of the piece of wood used, is to be excluded from the generalization; what is relevant, for example, the dryness of the wood, is to be included in it. […] The separation of relevant from irrelevant factors is the beginning of knowledge." (Reichenbach (1951/1968, p. 8).

A scientific explanation is not something that can be achieved easily: it "demands ample observation and critical thought; the higher the generality aspired to, the greater must be the mass of observational material, and the more critical the thought." (Reichenbach 1951/1968, p. 8) Any yet, as Reichenbach points out, "human beings are inclined to give answers even when they do not have the means to find correct answers." (Reichenbach (1951/1968, p. 8) As a result, they often develop pseudoexplanations. As explanations, pseudoexplanations are sets of beliefs people refer to in order to account for some phenomena. In Reichenbach's view, pseudoexplanations are false generalizations that do not identify the correct relationships between the phenomena (or their properties).

Even though all pseudoexplanations are false generalizations, they are not all equivalent. Some false generalizations are based on clear and well-defined descriptions of phenomena and can be considered to be "primitive scientific theories" that "lend themselves rather easily to correction and improvement in the light of further experience." (Reichenbach (1951/1968, p. 10) On the contrary, other pseudoexplanations are based on "superficial analogies, particularly analogies with human experiences" and on "loose language that creates false ideas" (Reichenbach 1951/1968, p. 8, 11). [5] When pseudoexplanations rely on ungrounded

[4] Even though this remains implicit in his paper, Reichenbach's analysis is inspired by a specific model of explanations, i.e. by the Hempel and Oppenheim's (1948) Deductive-Nomological Model. However, his description is general enough to also be compatible with other positions on what a scientific explanation consists of. The Deductive-Nomological Model of explanation does not explicitly rely on the notion of causation. But many advocates of this model argue that it still captures the causal component of explanations since "all causal claims imply the existence of some corresponding regularity (a "law") linking cause to effect" (Woodward 2017, cf. this article also for a brief discussion of the main modes of explanation that are currently under debate).

[5] Reichenbach suggests that – when people do not have the means to develop an actual explanation – they try to account for phenomena by analogy with something else they understand better: since human experience is something everybody has firsthand knowledge of, people usually resort to analogies with human experience. Reichenbach intuition on this is confirmed by a number of contemporary, empirical studies showing that people with a poor understanding of the physical word have a strong tendency to anthropomorphize. They tend to explain physical phenomena using the same principles they would use to explain the behavior of human agents and thus they project human-like characteristics onto non-human things (Epley, Waytz and Cacioppo 2007; Willard and Norenzayan 2013; Lindeman and Svedholm-Häkkinen 2016). And yet, the opposite also occurs, even if more rarely: people who exhibit a poor knowledge of the human mind and of social dynamics, but have a better comprehension of mechanisms and physical systems tend

analogies between phenomena spelled out in vague language, they become truly pernicious. Indeed, they introduce misleading factors that drive attention away from the relevant elements and relationships towards irrelevant one that can only with difficultly be proven wrong on the basis of theoretical analysis and empirical evidence.

From this point of view, Reichenbach's analysis is helpful for explaining why beliefs such as the belief in faith healing are particularly pernicious. These beliefs rely on inferential relationships that are difficult to spell out, to discuss from a theoretical point of view and to test on the basis of empirical evidence. If we follow Reichenbach in maintaining that people naturally tend to give explanations based on analogies with human experience, then this belief will probably be built on an anthropomorphization such as: someone who loves you, will help you, especially in things that are very important for you; God loves you; God is almighty; illnesses are very important for you; thus, God will heal you, if just you have faith in him (and thus show him your trust and love). A pseudoexplanation of this kind is very difficult to challenge because it relies - as Reichenbach suggests - on a superficial and ungrounded analogy with our ordinary experience and on entities, properties and relationships that cannot be discussed in the light of any scientific principle or that cannot be proven empirically, not even indirectly.

To sum up, this analysis provides some further answers for the questions raised at the beginning of this paper.

(i) Misconceptions always occur for a reason: they originate from an incorrect explanation of certain phenomena and are beliefs that depend on a number of other beliefs (inter alia pre-conceptions, naïve theories, vague commonsensical concepts) that are inferentially related to and support them.

(ii) By virtue of these inferential relationships, misconceptions interact with other beliefs; they are not inert elements in our belief system, but influence the way in which we reason and integrate new information.

(iii) Misconceptions can be more or less innocuous vs. pernicious depending on how easy or difficult it is to emend them. They are more difficult to fix and thus more pernicious (1) when they concern phenomena that cannot be observed; (2) when they are more widespread across our system of beliefs and we need to modify a larger set of beliefs to emend them; (3) when the set of beliefs that supports them diverges quite deeply from the explanations given by scientific theories and/or (4) when they rely on an explanation that is formulated in loose language and difficult to prove wrong on the basis of further reflection and observation. These four factors often co-occur and interact with each other in determining whether a misconception is more or less innocuous vs. pernicious, but they are still different and must be addressed separately.

In line with the framework we have outlined, misconceptions are very resistant to change because they are embedded in a belief system that, under certain conditions, can be quite difficult to alter. Moreover, they have a negative impact on a person's comprehension of new information because – when new knowledge is combined with a misleading system of inferences – this generates inconsistencies. Finally, misconceptions are typically expressed in vague and non-technical language and use superficial and vague descriptions because they often derive from pseudoexplanations that are based on our everyday experience which are intuitive and difficult to falsify.

to interpret human phenomena according to non-human but better known mechanical principles (Lindeman and Svedholm-Häkkinen 2016).

## 3. Two approaches to misconceptions: direct intervention vs. critical thinking

It is widely acknowledged that misconceptions are dangerous and detrimental. For this reason, many efforts have been made to develop intervention strategies that might help to overcome them. Even though misconceptions are widespread throughout the population and not even experts are free of them, most of the interventions that have been designed and put into practice in educational institutions have been aimed at students. This is unsurprising if we consider, on the one hand, that the very aim of education is to remove the obstacles that prevent people from learning reliable and well-grounded content and, on the other, that any possible action against misconceptions must be of an educational kind and can hardly be administered outside of institutional contexts. For this reason, the issue of how misconceptions can be overcome has been investigated almost uniquely in relation to students. Even though this might appear to be a limitation, in fact it is not. From a theoretical perspective, students are a particularly interesting subject of investigation because their knowledge is rapidly evolving. Thus, we can observe changes occurring in their belief systems as they acquire new disciplinary knowledge and develop better reasoning skills. From a practical point of view, students are the most significant subjects for this kind of study since – as already mentioned – any intervention we might implement to challenge misconceptions is of an educational kind; for this reason, no matter whom we address, this person will assume the role of a student.

According to a widely accepted view, (one of) the most effective ways to eradicate misconceptions is to intervene directly. The suggested approach consists in identifying the specific misconceptions students hold and drawing their attention to them: students must be told explicitly that these positions are wrong, and they should be instructed about the correct view. More specifically, to be incisive, teachers refute the prior erroneous beliefs by presenting evidence in support of the correct view (Manza et al 2010; McLean and Miller 2010; Guzzetti 2000; Kowalski and Taylor 2009; Furnham and Hughes 2014).

The reason why this strategy is considered to be the most effective is that it allows educators to achieve results in a short time: students rapidly change their minds, give up previous beliefs that are incompatible with their current scientific knowledge and embrace new scientifically supported beliefs instead. And yet this educational approach is risky: even though it might give results in the short term with respect to those specific beliefs explicitly discussed, its effect consists simply in persuading students to replace one belief with another without modifying the overall explanation of phenomena that supports their belief system. The new belief is accepted because it is transmitted and endorsed by a teacher (i.e. by virtue of an appeal to authority). However, because the teacher's action is aimed at modifying only one (or a few) specific belief(s) without taking into account the overall belief system it is/they are embedded in, the effect of the revision is only local and unstable.

This approach to misconception can be compared with so-called 'solution-focused brief therapy'. This 'brief therapy' against misconceptions corresponds quite closely to the example we discussed in the previous section concerning the misconception that it is possible to get pregnant from oral sex. If we limit ourselves to replacing this false belief with the correct one ('A girl *does not* get pregnant from oral sex') without challenging and globally modifying the way in which the person who held the misconception explains fertilization, this person will keep endorsing a number of different misconceptions related to the wrong explanation of fertilization s/he relies on. As suggested by Stein and colleagues, "to overcome existing misconceptions some kind of conceptual change has to occur in the student's mind." (Goris and Dyrenfurth 2010).

If the picture we outlined in the previous section is correct, the only truly incisive and effective way to address this misconception is to intervene in the explanation that supports it and adjust the system of inferences that

supports the misconception. By doing so, we act on all the interconnected false beliefs this person holds on the topic, give him/her good reasons to embrace new beliefs and provide him/her with adequate means to make further well-grounded and congruent inferences on related phenomena – i.e. to develop new insights into this content.

From this point of view, as an educational approach that aims to directly address students' misconceptions, 'solution-focused brief therapy' is not merely a catchy expression that underscores the rapid nature of its effects, but a meaningful metaphor. Solution-focused brief therapies work primarily by suppressing symptoms rather than addressing their cause. Of course, one cannot tackle a symptom without acting on some underlying mechanism correlated with it. And yet, the root causes may not be sufficiently addressed. When a therapy does not deal with the root causes, it often happens that new symptoms occur over time which are not identical but still very similar to previous ones. Indeed, these new symptoms result from the original systemic problems that now start to manifest their effects in slightly different forms (Kim 2008; Gingerich and Eisengart 2004; Bannink 2007). An analogous phenomenon occurs with the approach to misconceptions described above.

Misconceptions are the symptom of a more systematic underlying issue: they are relevant not only or primarily *per se*, but because they indicate that the people who endorse them rely on an incorrect explanation of the phenomena they describe. If the approach we adopt consists in addressing specific misconceptions, we will certainly remove them quite easily by explaining that they are wrong and why. However, if we do not challenge and improve the explanations these misconceptions are based on, others will arise in time which are not identical but still very similar to the previous ones, because they share the same origin. So, by focusing on specific misconceptions only, we suppress the symptom, but do not tackle the root cause, i.e. the deep reasons why people have come to embrace these misconceptions in the first place. To act on this deeper level, we must draw up a long-term strategy which addresses the global explanation of the phenomena at issue. To maximize its effect, this intervention should also bring people's attention to explanations in general and teach them what good explanations look like and how to obtain reliable evidence in support or against them. In this way, we will provide them with autonomous means to challenge and improve not only a particular explanation, but also the explanations they rely on.

An indirect and widely credited strategy to deal with misconceptions that fits this description goes under the name of critical thinking. At its very basis, critical thinking aims at improving students' analytic and evaluative attitudes toward knowledge and consists in a practice that trains individuals to reason in a disciplined manner, adhering to clear intellectual standards (see Wilson 2018). This includes a wide range of cognitive skills that allow people to approach the information they are confronted with in a critical manner and – among other things – to assess whether it should be accepted as true and why.

Critical thinking has established itself as a subject in many curricula and the content of such courses are fairly standardized, even though some aspects of the topic are still highly debated (for a general overview on critical thinking cf. Hitchcock 2018; for assessing critical thinking skills cf. Hitchcock 2018a). The definition of critical thinking as we know it today goes back to John Dewey (for a brief history of critical thinking starting from Dewey cf. e.g. Hitchcock 2017, p. 478-481). In his 1910 book *How we think* and a later extensively revised edition in 1933 *How We Think: A Restatement of the Relation of Reflective Thinking to the Educative Process*, Dewey described the troubles of the educational system of his time due to what we would today call the specialization of knowledge. In his view, what can restore stability and unity in spite of the multiplication of studies, materials and principles is a "scientific attitude of mind", what he calls "reflective thought" through which we deliberately and systematically search for the grounds of our beliefs. (Dewey 1910, p. 10 ff).

In Dewey's view, acritical thinking consists in a passive form of learning that leads to an accumulation of knowledge that is not accompanied by an adequate comprehension of how it should be organized and how the various pieces relate to form a system. The content is accepted as true only by virtue of the authority ascribed to the sources that convey it, without verifying whether there is adequate evidence to support it. The notion of critical thinking describes the opposite approach. Its main feature is *reflexivity*: this consists in an active form of knowledge acquisition in which immediate intuitions are weakened and put under scrutiny (Gil 2000). As Dewey describes it, reflection is a (necessary) individual disposition to not accept any belief content without verifying its truth conditions or without understanding the reasons that support it, i.e. without comprehending the (implicit and explicit) inferential relations that this content entertains with others. Any belief is considered to be the conclusion of an inferential process by which the reasons that motivate it have been assessed. Dewey's reflective thinking is described as critical because it involves the conscious participation of individuals who, in the process of verifying their beliefs, have considered the truth conditions and inferential processes that lead to them. Critical thinking is a habit of thought similar to a scientific attitude of mind that leads people to not accept belief content unless it has been properly weighted based on supporting evidence and until all alternative hypotheses have been considered. Until this inquiry is complete, any conclusion must be momentarily suspended, as happens in the verification process of new scientific content (Dewey 1910, p. 13 ff.; 1933, 179ff.).

Reflective thinking as described by Dewey is still a key element in critical thinking in its contemporary definition as an autonomous discipline characterized by a specific epistemology and by specific content (cf. e.g., Siegel 1989). A number of authors agree that critical thinking must be identified with a subjective attitude towards knowledge consisting in a particular form of open-mindedness that prevents people from blindly and dogmatically accepting beliefs and "involves fundamentally the evaluation of reasons on which belief and action are grounded" (Siegel 1989, p. 138; on this see also Ennis 1985). This notion of critical thinking does not merely *describe* a way of thinking, but it also has a *normative aim* which consists in identifying a complex of *good thinking practices and procedural standards*. They include the subjective attitude to continuously inspect the evidence we have in support of our beliefs and the reasons that justify them as well as the acquisition of specific capacities, competences and knowledge that allows us to follow correct procedures for inspecting evidence and reasons.

This way of interpreting critical thinking includes, first of all, an important cognitive component in which critical thinking denotes a form of metacognition and can be described as an "effortful and consciously controlled" way of thinking (Halpern 2014, p. 8ff.). In fact, critical thinkers must be able to achieve a high level of control over their cognitive processes and their reasoning in order to continuously monitor the level of clarity, consistency and reliability of their belief content. However, critical thinking cannot merely consist in a form of metacognitive monitoring because, in order to exercise conscious control of our thinking processes so that we can verify the reliability of our beliefs (the evidence they rely on and the inferences that lead to them), we also need to acquire specific capacities and knowledge. We need, in particular, to learn how to assess *whether a belief is based on reliable evidence* and (2) *whether the arguments that support it are congruent and strong*.

As for the first factor mentioned, in order to assess whether a belief is based on reliable evidence, it is essential to gain adequate "background knowledge" of the subjects we must assess (Bailin et al. 1999a, 1999b; Bailin 2002). Among other things, we must be able to identify and evaluate the sources of the knowledge we have and rely on (Kahane 1989). This allows us to make sure that we have not accepted this knowledge only on the basis of an appeal to authority, for example, because we blindly trusted a certain source (Cottrell 2005; Rainbolt and Dwyer 2012). As for the second factor we pointed to, in order to evaluate

whether the arguments that support a belief are congruent and strong, we need to acquire specific competences related to the *theory of argumentation*, the *theory of reasoning and logic*. The complex of these competences is typically considered to be the specific knowledge required to think critically: the tools needed by the critical thinker (Bailin et al. 1999b, p. 293-294).

The *theory of reasoning and logic* represent essential resources, for example, for understanding the correct use of logical operators as well as fundamental principles such as the law of contradiction, the excluded middle and the principle of identity. This knowledge allows us to avoid common mistakes in everyday reasoning such as the conjunction and disjunction fallacies. Understanding these implications also facilitates the acquisition of notions such as necessary and sufficient conditions which are, in turn, fundamental for understanding causal reasoning (direct cause, proximate cause, contributing cause, correlational relationships, and so on). By studying these subjects, people also become familiar with the most important valid forms of reasoning (e.g. *modus ponens* and *modus tollens*, disjunctive syllogism). The capacity to solve logic puzzles might also be quite useful for critical thinking. In fact, even though solving such puzzles is sometimes considered excessively abstract and virtual (Govier 1989), this capacity requires learning how to identify the information available in a certain context, how to univocally define and organize this information (given that in natural language it is typically expressed in an imprecise, incomplete and disorganized manner), how to recognize what is actually relevant in that given context and how to represent this information in the best way (e.g. by using a matrix, a graph, a Eulero or Venn diagram, etc.) so that we can assess the relations among the different pieces of information and draw relevant conclusions.

The *theory of argumentation* provides people with the instruments they need to analyze arguments, i.e. to understand how certain premises support certain conclusions which we may end up accepting or rejecting. To assess the quality of an argument we need to gain knowledge concerning, among others, the validity and invalidity of arguments, the relevance of the premises with respect to the conclusions, and, in the case of inductive arguments, the strength of the argument (i.e. the probability that a conclusion is true, given the evidence offered by the premises), and the vulnerability of the conclusion to possible changes in the evidence offered in the premises. More generally, we must learn how to distinguish between arguments and non-arguments as well as between good and bad arguments. In assessing arguments, it is particularly relevant to acquire the specific instruments offered by a subdiscipline of the theory of argumentation and informal logic called *argument analysis*. By studying argument analysis, students learn how to summarize, paraphrase and diagram arguments in order to clearly identify their logical structure and thus to reveal the inferential links among the various elements that form the argument. Diagramming arguments is essential, among other things, in order to identify what axioms occur in the argument, that is, in order to pinpoint the statements (content) that are assumed to be true and are used to justify further statements (content) without themselves being proven by other statements within the argument. In this way, we can evaluate both whether the argument is internally and externally consistent, i.e., whether the various statements are consistent with each other and with the axioms and whether the axioms are consistent with evidence that is available independently of the argument.

In summary, critical thinking is a complex discipline that consists in a plurality of factors:

(a) an open-minded attitude that fosters individuating and analyzing the evidence in support of our beliefs and repeatedly questioning this evidence to verify its reliability;

(b) procedural abilities and competencies needed to identify and logically organize the relevant information in a certain context; and

(c) specific knowledge of the various topics at issue that allow people to verify the various statements that form the argument as well as their relevance (also in comparison to others) for the conclusion.

Critical thinking is considered to be an effective tool against erroneous beliefs such as misconceptions because these are considered to be the product of a non-evidential style of thought (Siegel 2009), in which people passively accept information they are exposed to without further questioning or investigating it or examining how it relates to other known information.

## 4. Why do we need critical thinking?

"Give a man a fish and you feed him for a day; teach a man to fish and you feed him for a lifetime." This old saying is meant to draw our attention to autonomy and it does not apply only to fish but also to knowledge. A truly incisive therapy for misconceptions should not only help us correct a specific misconception or even a specific explanation that gives rise to particular misconceptions but should give us the means to epistemologically assess any new explanation we encounter and evaluate whether it is well-grounded.

This is a fairly abstract capacity and it is certainly open to discussion what kind of educational path would lead people to develop it. However, at least certain basic knowledge appears indispensable. In the previous section, we argued that critical thinking might be the discipline that can offer this kind of knowledge. Here we say something more on this topic and specify the reasons why the instruments offered by critical thinking are essential for this therapy.

A good place to start dealing with this issue is the procedural abilities and competencies one acquires in the study of logic, theory of reasoning and theory of argumentation (b). As clearly shown not only in everyday teaching practice but also by a number of studies in the field of the psychology of reasoning, people's logical capacities are very limited; they are prone to a number of errors and biases (think, for example, of the famous 'conjunction fallacy' or 'Linda problem', cf. Tversky and Kahneman 1983; for a more general overview cf. Kahneman 2011). The literature on this is immense and cannot be summarized here. However, it is worth mentioning that – when people rely on their spontaneous intuitions and lack specific training in logic – they do not pay very much attention to the correctness of the inferential procedure they follow, and draw their own conclusions merely on the basis of the contents they are reasoning about. One could say that they are blinded by the contents and do not see the procedure (Brosnan et al. 2016; De Martino et al. 2008).

Consider the following example: "All flowers need water. Roses need water. Therefore, roses are flowers" (Brosnan et al. 2017). People who have never learned the basics of logic or first-time students typically say that this argument is valid. They jump to this conclusion on the basis of their real-world experience: in this case, because both the premises and the conclusion are true, they think that the reasoning process must be correct. The very same phenomenon occurs when we have to deal with numbers. The following example was discussed in by Todd (2018):

$$\frac{16}{64} = \frac{1\cancel{6}}{\cancel{6}4} = \frac{1}{4}$$

People with poor mathematical training agree that there is nothing wrong with this process and that 16/64 = 1/4 *because* you can simplify or reduce the fraction by eliminating the 6 in both the numerator and the

denominator. People with at least a basic mathematical training immediately notice that there is something wrong in the process even though it is true that 16/64 = 1/4.

The point of these examples is that – when we are not specifically trained to pay attention to reasoning procedures – we overlook them in favor of the contents we are reasoning about. *Therefore, reasoning procedures, logic and argumentation must be the object of a specific type of knowledge and in particular they must be explicitly taught and trained.* The study of critical thinking allows people not only to acquire these procedural capacities, but also to train using concrete examples expressed in natural language and see how such procedures work and why they are useful in practice. When we study formal logic, the need to formalize leads us to move away from natural language and from its ambiguities and thus avoid real arguments in their often ambiguous and imprecise forms. Moreover, we do not need to formalize real arguments in order to understand them: people who do not grasp formalization can also learn to analyze arguments by using informal means. Critical thinking is a way to acquire procedural capacities of this kind without falling into the trap of formalization.

The second aspect of critical thinking that needs to be explored more closely concerns the knowledge of the topics at issue and, in the case of misconceptions, specifically of the relevant scientific facts (c). Some descriptions of this discipline do not place a great emphasis on the scientific/disciplinary content that people must acquire in order to gain the ability to think critically about them. Even though in the previous analysis we underscored the importance of the reasons we have to hold our beliefs, i.e. the explanations we give for them and the arguments we use in support of them, we cannot consider these reasons independently of the contents they underpin. Explanations and arguments are not just empty structures and we cannot assess whether a reason to hold a belief is good or bad if we do not know what we are talking about.

If we only train students to deal with formal structures and with abstract procedures for analyzing arguments and explanations, they will hardly be able to address concrete, domain specific knowledge. As pointed out, for example, by Bailin (2002, p. 366), "the very notion of thinking processes which are separate from knowledge is highly questionable. For example, it makes no sense to refer to a process of interpreting which remains constant regardless of the subject matter." Thus, "background knowledge in a particular area is a precondition for critical thinking to take place" (Bailin et al. 1999a, p. 271) and a person will not become a critical thinker unless s/he learns the relevant scientific/disciplinary contents.

One of the approaches that has been proposed to jointly develop thinking skills and disciplinary knowledge is the "'infusion' approach, in which the development of thinking is infused within disciplinary courses." (Zohar, Weinberger and Tamir 1994, p. 183-184). The infusion approach can be used in all kind of courses, but it is usually implemented in research methods courses (Stark 2012; Burke et al. 2014). This approach aims to incrementally develop the quality of students' reasoning by training them to critically examine particular domain-specific theories in light of the research methods used within the discipline. Critical thinking-infused research methods might be particularly incisive for assessing empirical evidence in support of certain domain specific contents and their reliability. However, if taught separate from other knowledge that forms part of critical thinking as we have described it – and in particular from teaching procedural abilities and competencies and an open-minded attitude – they lose efficacy. In fact, methodological reflections on disciplinary contents neither provide students with the tools to understand how explanations are structured, how arguments are organized, and whether they are strong or weak, nor do they develop a critical attitude that leads to questioning scientific evidence again and again. It is the study and exercise of the whole discipline of critical thinking that – jointly with the acquisition of domain specific contents – leads people to critically reflect on the theories they learn so that they become capable and are motivated to evaluate the evidence these rely on and the arguments in support of them.

This open-minded attitude is indeed the third aspect of critical thinking we need to consider (a). In a well-known passage that presages the notion of critical thinking, William G. Sumner in his 1906 book "Folkways" writes: "Schools make persons all on one pattern, orthodoxy. School education, unless it is regulated by the best knowledge and good sense, will produce men and women who are all of one pattern, as if turned in a lathe. An orthodoxy is produced in regard to all the great doctrines of life. It consists of the most worn and commonplace opinions which are common in the masses. The popular opinions always contain broad fallacies, half-truths, and glib generalizations […] Criticism is the examination and test of propositions of any kind which are offered for acceptance, in order to find out whether they correspond to reality or not. The critical faculty is a product of education and training. It is a mental habit and power" (Sumner 1906, p. 630ff.).

The "mental habit and power" Sumner speaks of is an attitude of mind that aims to prevent indoctrination understood as the development of erroneous beliefs based on incorrect or superficial information. Thus, ever since it started, critical thinking has been conceived not just as a complex of capacities and knowledge, but also as a general disposition that requires motivation and training for its initial formation. This attitude is characterized by multifaceted factors. First of all, it requires a certain humility toward the evidence we have gathered in support of our beliefs (Russell 1960; see also Hare 2001) that should lead us to question it repeatedly and to integrate it over time; in other terms, critical thinkers should always be willing "to revise and reconsider their views" (Hare 1979, p. x) Secondly, it consists in a capacity to control and avoid any form of automatic thinking which typically leads us to recall and confirm information we already have, to repeat inferences we made in the past as a matter of routine, or to jump to conclusions (Halpern 2014, p. 7ff.). This open-mindedness – i.e. this critical and reflexive disposition – is not natural for human beings who tend, on the contrary, to think on the basis of automatic intuitions, to repeat the same thinking processes over and over again and to have strong confirmation biases (Maynes 2015). Thus, the study of critical thinking is essential in order to form the initial disposition to think critically about any issue and to develop the internal disposition to keep reasoning in a critical manner across the entire assessment process of any issue we consider (Facione 1990, p. 25).

Our discussion up until this point has explained why critical thinking is needed in order to acquire capacities, knowledge and attitudes that we do not naturally have and that we need to learn and to do science and – more generally – to avoid ignorance due to indoctrination or accepting pieces of knowledge which haven't been verified or incorporated in an appropriate explanation. However, we have not yet addressed the specific issue of how critical thinking might help us to overcome misconceptions. To answer this question, it is useful to go back to the examples of misconceptions we considered previously and to reexamine them in the light of what we said about critical thinking.

Relying on Reichenbach, we differentiated between erroneous beliefs that are fairly innocuous and easier to dispel and beliefs that are more pernicious and difficult to correct and we qualified 'Kathmandu is the capital of Peru' as belonging to the first class. Even though this misconception is particularly simple, critical thinking is still useful in addressing it in an at least twofold manner. On the one hand, critical thinking instills in us the attitude to check our beliefs again and again in the light of available evidence and it teaches us not to assume that they are true only by virtue of the fact that they are familiar to us; that we have been holding these beliefs for a long time and feel sure about them. On the other hand, as we mentioned before, this belief might derive from a wrong inference of the kind that 'Kathmandu is the capital of some poor country' and 'Peru is a poor country'. Through argument analysis (which is a part of critical thinking), we become aware of the inferences we make and the reasons why we believe something. Thus, we can more easily examine the weak points in our reasoning processes and, in this case for example, establish that – knowing that

Kathmandu is the capital of some poor country and that Peru is a poor country – are not good reasons to believe that Kathmandu is the capital of Peru.

The role of critical thinking is all the more important when we consider pernicious cases of misconceptions. A first example of this type we discussed concerns the belief that 'A girl can get pregnant from oral sex'. This belief derives from an incorrect explanation of reproduction in which fecundation occurs whenever sperm (or, more generally, bodily fluids) come into contact with any part (or penetrate any orifice) of a woman's body. Critical thinking does not say anything specific about reproduction, of course, even though it teaches people to always base their conclusions on scientific, well-grounded knowledge. However, the most important way in which we benefit from critical thinking in cases like this relates to the very structure of arguments and explanations. If we know what strong and congruent arguments and explanations look like, we can examine the structure of our own explanations and become aware of whether they are sufficiently clear or based on sufficient knowledge and whether alternative explanations are possible. In this case, many explanations are possible and to choose among them we must establish how the events are causally interconnected with each other: to recognize what a good explanation looks like allows us to assess that our explanation of reproduction is weak and that we need to find out what the relevant causal chain is.

This example might not be the best for showing the relevance of critical thinking for misconceptions because the theory of reproduction is something adults typically know very well (yet, the mentioned misconception is widespread among teenagers: Wynn, Foster and Trussell 2009). Thus, it appears to be quite easy to overcome such misconceptions simply through social learning. However, if we apply the principle we started with in this section– "teach a man to fish and you feed him for a lifetime" – then it appears more clear that we need to acquire general means that allow us to autonomously assess any explanation and argument we are confronted with from the point of view of possible alternatives as well as intrinsic weaknesses and strengths. This allows us to establish whether we are justified in believing that we actually know something simply because we have good reasons to support this belief.

A similar point can be made with relation to the other example we offered of an even more pernicious belief: faith healing. In fact, argument analysis allows us to identify the deep structure of all kind of arguments, and in particular the explicit and implicit premises, including axioms and axiological grounds (i.e. the non-logical factors related to values that influence an argument). In this case, the problematic axiom concerns the existence of God, the belief that God intervenes in human affairs and that He rewards faith. Considering that these premises cannot be assessed empirically, but depend on people's cultural legacy and values, at first glance it appears that critical thinking is helpless before a supernatural belief such as faith healing. However, to be aware of the explanatory structure at the basis of our beliefs and the arguments we rely on always offers significant advantages. First of all, we become aware that our beliefs and explanations violate the natural causal principles described by the sciences. Secondly, the analysis of these premises prompts us to reflect that the axioms our arguments rely on can be held to be true only by virtue of an appeal to the authority of a superior source, but not on the basis of empirical evidence. Finally, we can reflect on the fact that – even though our explanation might be internally consistent – it is inconsistent and incompatible with others that are based on a natural form of causality and with current empirical evidence and we can then compare and assess these explanations from various points of view.

More generally, critical thinking leads us to improve our scientific knowledge as well as our knowledge of the procedures reasoning is based upon and it enforces an open-minded attitude. These three factors together enhance the *self-correcting character* of our thought and our capacity to ask the right questions to challenge previous beliefs (Browne and Keeley 2007, p. 53ff.). The acquisition of a modest and non-dogmatic attitude toward what we believe allows us to revise previous conclusions because the reasons we had to hold them

have changed. For a critical thinker, beliefs are never necessarily and inevitably true, but are accepted only provisionally (Govier 2010, p. 127-128): they must always be further scrutinized and can always be confuted by new (counter)arguments. The sense of critical thinking is that nothing is ever certain and can be taken for granted. In that spirit, non-empirical axioms and axiological grounds can also be called into question and continuously examined, rationally and reflexively.

## 5. Concluding remarks

Ignorance – this is the point we started with – is not solely or primarily due to some missing or incorrect pieces of information. In fact, knowledge does not merely consist in a pile of disconnected facts: to become knowledge, these pieces need to be tied together in just the right way. Both knowledge in general as well as individual beliefs are made up of parts (contents) that are connected to each other in a system of inferential relationships. These relationships constitute our reasons for believing what we believe. Thus, to remedy our false beliefs we must understand how our belief system is structured and act on it by modifying the inferential structure of these reasons. Some false beliefs might be produced by correct explanations because of some mistake of minor importance: in this case, they remain marginal to the system and can be easily corrected. However, other false beliefs may derive from pseudo explanations: these are more central to the system and to emend them we must change larger parts of the system. Thus, ignorance – as we said – is not something that can be assessed categorically (either one is ignorant about something or one is not), but occurs in degrees which depend on the size of the part of our belief system that is affected by a pseudo explanation and thus how difficult it is to remedy our false beliefs. As with any kind of false beliefs, misconceptions (understood in general as incorrect scientific beliefs) may be more marginal to the system and thus be less difficult to rectify or may depend on pseudo explanations and be more pernicious and harder to fix. In this article, we have discussed various examples of misconceptions belonging to these two types and the differences between them.

As for the most appropriate strategy for overcoming misconceptions – and in particular misconceptions of the pernicious kind – we challenged a direct approach which aims at criticizing them individually and offering supporting evidence for the correct view. We argued that this approach addresses the symptom (the false belief) without tackling the causes, i.e. without considering the reasons people have for holding their misconceptions. We suggested that – in order to act on the causes – people must learn what explanatory structures and arguments look like, how these structures can be made explicit and how they can be compared to each other in order to assess their weaknesses and strengths and thus establish which one should be preferred over the others. The discipline that in our view leads people to develop the kind of knowledge that is required for such assessments is critical thinking, understood as a blend of an open-minded attitude, the knowledge of specific thinking procedures (especially related to argumentation theory and informal logic) and scientific knowledge of the content that is the object of our reflection.

What emerges from the discussion of how critical thinking can help us remedy misconceptions is a perspective on ignorance that views it as the result of a *nonevidential style of belief-formation*. Critical thinking appears to be key to developing integrated and coherent belief systems that are continuously examined from the point of view of the evidence they rely on and that are evaluated over and over again to assess their plausibility with respect to others. An evidential style of belief-formation is also the only means we have to walk out of the circle of our beliefs and to reverse the tendency we have to confirm what we already believed in the first place and to accept all and only information that is congruent with it.

## References


Aarnio, K. & Lindeman, M. (2005). Paranormal beliefs, education, and thinking styles. *Personality and Individual Differences*. *39(7)*: 1227-1236. doi: 10.1016/j.paid.2005.04.009.

Bailin, S, Case, R., Coombs, J.R. & Daniels, L.B. (1999b). Conceptualizing critical thinking. *Journal of Curriculum Studies*. *31(3):* 285-302. doi: 10.1080/002202799183133.

Bailin, S. (2002). Critical thinking and science education. *Science and Education*. *11(4)*: 361-375. doi: 10.1023/A:1016042608621.

Bailin, S., Case, R., Coombs, J. R., & Daniels, L. B. (1999a). Common misconceptions of critical thinking. *Journal of Curriculum Studies*. *31(3)*: 269-283. doi: 10.1080/002202799183124.

Bannink, F. P. (2007). Solution-focused brief therapy. *Journal of Contemporary Psychotherapy*. *37(2)*: 87-94. doi: 10.1007/s10879-006-9040-y.

Bensley, D. A., & Lilienfeld, S. O. (2010). The test of psychological knowledge and misconceptions.

Bensley, D.A., & Lilienfeld, S.O. (2015). What is a psychological misconception? Moving toward an empirical answer. *Teaching of Psychology*. *42(4):* 282-292. doi: 10.1177/0098628315603059

Bensley, D.A., Lilienfeld, S.O., & Powell, L.A. (2014). A new measure of psychological misconceptions: Relations with academic background, critical thinking, and acceptance of paranormal and pseudoscientific claims. *Learning and Individual Differences*. *36:* 9-18. doi: 10.1016/j.lindif.2014.07.009

BonJour, L. (1985). *The structure of empirical knowledge*. Cambridge, MA: Harvard University Press.

Brosnan, M., Lewton, M., & Ashwin, K. (2016). Reasoning on the autism spectrum: A dual process theory account. *Journal of Autism and Developmental Disorders. 46*: 2115-2125.

Brosnan, M., Ashwin, C., & Lewton, M. (2017). Brief Report: Intuitive and reflective reasoning in Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders. 47(8):* 2595-2601. doi: 10.1007/s10803-017-3131-3

Browne, N.M. & Keeley, S.M. (2007). *Asking the right questions*. Upper Saddle River: Prentice-Hall.

Burke, B.L., Sears, S.R., Kraus, S. & Roberts-Cady, S. (2014). Critical analysis: A comparison of critical thinking changes in psychology and philosophy classes. *Teaching of Psychology*. *41(1)*: 28-36. doi: 10.1177/0098628313514175.

Conception (2011). In Merriam-Webster.com. Retrieved August 17, 2019, from https://www.merriam-webster.com/dictionary/conception

Cottrell, S. (2005). *Critical Thinking skills. Developing effective analysis and argument*. New York: Palgrave.

Davidson, D. [1982] (2004). Paradoxes of irrationality. In D. Davidson, *Problems of irrationality* (pp. 169-187). Oxford/New York: Oxford University Press.

Davidson, D. [1985] (2004). Incoherence and irrationality. In D. Davidson, *Problems of irrationality* (pp. 189-198). Oxford/New York: Oxford University Press.

Davidson, D. [1986] (2004). Deception and division. In D. Davidson, *Problems of irrationality* (pp. 199-212). Oxford/New York: Oxford University Press.

De Martino, B., Harrison, N. A., Knafo, S., Bird, G., & Dolan, R. J. (2008). Explaining enhanced logical consistency during decision making in autism. *Journal of Neuroscience. 28(42):* 10746-10750. doi:10.1523/JNEUROSCI.2895-08.2008.

De Rosa, R., & Lepore, E. (2004). Quine's meaning holisms. In R.F. Gibson (ed.). *The Cambridge companion to Quine* (pp. 65-90). Cambridge: Cambridge University Press.

Dewey, J. (1910). *How we think*. Boston/New York/Chicago: D.C. Heath.

Dewey, J. (1933). *How we think: A restatement of the relation of reflective thinking to the educative process.* Lexington (MA): D.C. Heath.

di Sessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 88-108). Cambridge: Cambridge University Press.

Elgin, C. (2005). Non-foundationalist epistemology: Holism, coherence, and tenability. In M. Steup, E. Sosa (eds.). Contemporary debates in epistemology (pp. 156-167). New York/London: Blackwell.

Ennis, R.H. (1985). A logical basis for measuring critical thinking skills. *Educational Leadership*. *43(2)*: 44-48.

Ennis, R.H. (1996). *Critical thinking*. Prentice-Hall: Upper Saddle River.

Epley N., Waytz A., & Cacioppo J.T. (2007). On seeing human: a three-factor theory of anthropomorphism. *Psychological Review. 114(4):* 864-886.

Facione, P.A. (1990). *Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction*, Research Findings and Recommendations Prepared for the Committee on Pre-College Philosophy of the American Philosophical Association, ERIC Document ED315423.

Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford: Stanford University Press.

Firestein, S. (2012). *Ignorance: How it drives science*. Oxford: Oxford University Press.

Fischer, K.M. (1983). Amino Acids and Translations: A Misconception in Biology. In H. Helm, J.D. Nowak (eds.), *Proceedings of the international seminar on misconceptions in science and mathematics* (pp. 407-419). Ithaca (NY): Cornell University Press.

Fodor, J.A., Lepore, E. (1992). *Holism: A shopper's guide*. USA, UK: Blackwell.

Furnham, A., & Hughes, D. J. (2014). Myths and misconceptions in popular psychology: Comparing psychology students and the general public. *Teaching of Psychology. 41*(3): 256-261.

Gardner, R., & D.L. Brown (2013). A test of contemporary misconceptions in psychology. *Learning and Individual Differences. 24*. 211-215. doi: 10.1016/j.lindif.2012.12.008.

Garnett, P.J., & Treagust, D.F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science and Teaching. 29(2)*: 121-142.

Garnett, P.J., & Treagust, D.F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science and Teaching. 29(10)*: 1079-1099.

Gil, F. (2000). *La conviction*. Paris: Flammarion.

Gilbert, J.K., & Watts, D.M. (2008). Concepts, misconceptions and alternative conceptions: Changing perspective in science education. *Studies in Science Education. 10(1)*: 61-98.

Gingerich, W.J., & Eisengart, S. (2004). Solution-focused brief therapy: A review of the outcome research. *Family Process*. *39(4):* 477-498. doi:10.1111/j.1545-5300.2000.39408.x.

Goris, T., Dyrenfurth, M. (2010). Students' misconception in science, technology, and engineering. Conference paper available at <http://ilin.asee.org/Conference2012/Papers/Goris.pdf>.

Govier, T. (1989). Critical thinking as argument analysis?. *Argumentation. 3(2)*: 115-126. doi:10.1007/BF00128143

Govier, T. (2010). *A practical study of argument*. Cengage: Wadsworth.

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

Guzzetti, B. J. (2000). Learning counter-intuitive science concepts: What have we learned from over a decade of research?. *Reading & Writing Quarterly*. *16(2):* 89-98.

Halpern, D. F. (2014). *Thought and knowledge. An introduction to critical thinking*. New York: Psychology Press.

Hare, W. (1979). *Open-mindedness and Education*. Kingston: McGill-Queen's University Press.

Hare, W. (2001). Bertrand Russell and the ideal of critical receptiveness. *Skeptical Inquirer*. *25(3)*: 40-44.

Harman, G. (1993). Meaning holism defended. In: Fodor, J.A., Lepore, E. (eds.). *Holism: A consumers update* (pp. 163-171). Amsterdam: Rodopi.

Hempel, C., & Oppenheim, P. (1948). Studies in the Logic of Explanation. *Philosophy of Science. 15*: 135-175.

Herron, J.D. (1990). Research in chemical education: Results and directions. In: M. Gardner, J.G. Greeno, F. Reif, A.H. Schoenfaled, A.A. di Sessa, E. Stage (eds.), *Toward a scientific practice of science education* (pp. 31-54). Hillsdale (NJ): Erlbaum.

Hitchcock, D. (2017). *On reasoning and argument: Essays in informal logic and on critical thinking.* Dordrecht: Springer. doi:10.1007/978-3-319-53562-3_30.

Hitchcock, D. (2018a). Critical thinking. In E.N. Zalta (ed.). *The Stanford encyclopedia of philosophy.* URL = <https://plato.stanford.edu/archives/fall2018/entries/critical-thinking/>.

Hitchcock, D. (2018b). Assessment. Supplement to critical thinking. In E.N. Zalta (ed.). *The Stanford encyclopedia of philosophy.* URL = https://plato.stanford.edu/entries/critical-thinking/assessment.html

Irwin, H.J. (2009). *The psychology of paranormal belief. A researcher's handbook*. Hatfield: University of Hertfordshire Press.

Kahane, H. (1989). The proper subject matter for critical thinking courses. *Argumentation*. *3(2)*: 141-147.

Kahneman, D. (2011). *Thinking, fast and slow*. New York: Farrar, Strauss & Giroux.

Kendeou, P., & van den Broek, P. (2005). The effects of readers' misconceptions on comprehension of scientific text. *Journal of Educational Psychology. 97(2)*: 235-245. doi: 10.1037/0022-0663.97.2.235.

Kikas, E. (2004). Teachers' conceptions and misconceptions concerning three natural phenomena. *Journal of Research in Science Education. 41(5)*: 432-448.

Kim, J. S. (2008). Examining the effectiveness of solution-focused brief therapy: A meta-analysis. *Research on Social Work Practice*. *18(2):* 49-64. doi:10.1177/1049731507307807.

Kirby, G. (2018). *Wacky and wonderful misconceptions about our universe*. Berlin/Heidelberg: Springer.

Kowalski, P., & Taylor, A. (2009). The effect of refuting misconceptions in the introductory psychology class. *Teaching of Psychology*. *36(3)*: 153-159.

Kuczmann, I. (2017). The structure of knowledge and students' misconceptions in physics. *AIP Conference Proceedings.* 1916, 050001. doi:10.1063/1.5017454.

Le Morvan, P. (2011). On ignorance: A reply to Peels. *Philosophia*. *39(2)*: 335-344.

Le Morvan, P. (2012). On ignorance: A vindication of the standard view. *Philosophia*. *40(2)*: 379-393.

Le Morvan, P. (2013). Why the standard view of ignorance prevails. *Philosophia*. *41(1)*: 239-256.

Le Morvan, P., & Peels, R. (2016). The nature of ignorance: Two views. In R. Peels & M. Blaauw (Eds.), *The Epistemic Dimensions of Ignorance* (pp. 12-32). Cambridge: Cambridge University Press. doi:10.1017/9780511820076.002

Lindeman, M., & Aarnio, K. (2007). Superstitious, magical, and paranormal beliefs: An integrative model. *Journal of Research in Personality. 41(4)*: 731-744.

Lindeman, M., & Svedholm-Häkkinen, A.M. (2016). Does poor understanding of physical world predict religious and paranormal beliefs?. *Applied Cognitive Psychology*. *30(5)*: 736-742. doi: 10.1002/acp.3248

Manza, L., Hilperts, K., Hindley, L., Marco, C., Santana, A., & Vosburgh Hawk, M. (2010). Exposure to science is not enough: The influence of classroom experiences on belief in paranormal phenomena. *Teaching of Psychology*. *37(3)*: 165-171.

Maynes, J. (2015). Critical thinking and cognitive bias. *Informal Logic. 35(2)*: 183-203.

McLean, C.P. & Miller, N.A. (2010). Changes in critical thinking skills following a course on science and pseudoscience: A quasi-experimental study. *Teaching of Psychology*. *37(2):* 85-90.

Nottelmann, N. (2016). The varieties of ignorance. In R. Peels, M. Blaauw (Eds.), *The epistemic dimensions of ignorance* (pp. 33-56). Cambridge: Cambridge University Press. doi:10.1017/9780511820076.003.

Özmen, H. (2004). Some student misconceptions in chemistry: A literature review of chemical bonding. *Journal of Science Education and Technology. 13(2)*: 147-159. doi: 10.1023/B:JOST.0000031255.92943.6d.

Peels, R. (2010). What is ignorance?. *Philosophia*. *38(1)*: 57-67.

Peels, R. (2011). Ignorance is lack of true belief: A rejoinder to Le Morvan. *Philosophia*. *39(2)*: 345-355.

Peels, R. (2012). The new view on ignorance undefeated. *Philosophia*. *40(4)*: 741-750.

Pennycook, G., Cheyne, J.A., Seli, P., Koehler, D.J., & Fugelsang J.A. (2012). Analytic cognitive style predicts religious and paranormal belief. *Cognition*. *123(3)*: 335-346. doi:10.1016/j.cognition.2012.03.003.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education. 66(2)*: 211-227.

Potvin, P., Cyr, G. (2017). Toward a durable prevalence of scientific concept: Tracking the effects of two interfering misconceptions about buoyancy from preschoolers to teachers. *Journal of Research in Science Teaching. 54(9)*: 1121-1142.

Pressman, M.R. (2011). Common misconceptions about sleepwalking and other parasomnias. *Sleep Medicine Clinics*. *6(4)*: xiii-xvii.

Quine, W. v.an O., & Ullian, J.S. (1970). *The web of belief*. New York: Random House.

Quine, W.v.O. (1951). Two dogmas of empiricism. *Philosophical Review. 60:* 20-43.

Rainbolt, G.W., & Dwyer, S.L. (2012). *Critical thinking. The art of argument*. Boston: Wadsworth.

Reichenbach, H. [1951] (1968). *The rise of scientific philosophy*. Berkeley/Los Angeles: University of California Press.

Russell, B. (1960). *Our knowledge of the external world*. Mentor: New York.

Sanger, M.J., & Greenbowe, T.J. (1997). Common students' misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching. 34(4)*: 377-398.

Siegel H. (2009), Open-mindedness, critical thinking, and indoctrination: Hommage to William Hare. *Paideusis*. *18(1)*: 26-34.

Siegel, H. (1988). *Educating reason: Rationality, critical thinking and education*. New York/London: Routledge.

Siegel, H. (1989). Epistemology, critical thinking, and critical thinking pedagogy. *Argumentation*. *3(2)*: 127-140.

Simpson, W. D., & Marek, E. A. (1988). Understandings and misconceptions of biology concepts held by students attending small high schools and students attending large high schools. *Journal of Research in Science Teaching*. *25(5)*: 361-364.

Smith, J.P., di Sessa, A.A., & Roschelle, J. (1994). A constructivist analysis of knowledge in transition. *Journal of the Learning Science 3(2)*:115-163.

Smithson, M. (1989). *Ignorance and uncertainty. Emerging paradigms*. New York/Berlin: Springer

Stark, E. (2012). Enhancing and assessing critical thinking in a psychological research methods course. *Teaching of Psychology*. *39(2)*: 107-112. doi: 10.1177/0098628312437725

Stein, M., Larrabbee, T.G., & Barman, C.R. (2008). A study of common beliefs and misconceptions in physical science. *Journal of Elementary Science Education*. *20(2)*: 1-11.

Steup, M. (2018). Epistemology. In: E. N. Zalta (ed.). *The Stanford encyclopedia of philosophy* URL = <https://plato.stanford.edu/archives/win2018/entries/epistemology/>.

Sumner, W.G. (1906). *Folkways. A study of the sociological importance of usage, manners, customs, mores, and morals*. Boston (MA): Ginn.

Taylor, A. K., & Kowalski, P. (2014). Student misconceptions: Where do they come from and what can we do?. In V. A. Benassi, C. E. Overson, C. M. Hakala (Eds.), *Applying science of learning in education: Infusing psychological science into the curriculum* (pp. 259-273). Washington: Society for the Teaching of Psychology.

Taylor, A., & Kowalski, P. (2004). Naive psychological science: The prevalence, strength and sources of misconceptions. *Psychological Record*. *54(1)*: 15-25.

Taylor, A.K & Kowalski, P. (2012). Students' misconceptions in psychology: How you ask matters… sometimes. *Journal of the Scholarship of Teaching and Learning*. *12(3)*: 62-72.

Thagard, P. (2000). *Coherence in thought and action*. Cambridge, London: MIT press.

Thagard, P. (2007). Coherence, truth, and the development of scientific knowledge. *Philosophy of Science 74 (1)*: 28-47.

Todd, C. (2018). Fitting feelings and elegant proofs: On the psychology of aesthetic evaluation in mathematics. *Philosophia Mathematica. 26(2)*: 211-233. doi: 10.1093/philmat/nkx007

Tversky, A. & Kahneman, D. (1983). Extension versus intuitive reasoning: The conjunction fallacy in probability judgment. *Psychological Review*. *90(4)*: 293-315. doi:10.1037/0033-295X.90.4.293.

van Cleve, J. (2005). Why coherence is not enough: A defense of moderate foundationalism. In M. Steup, E. Sosa (eds.). Contemporary debates in epistemology (pp. 168-180). New York/London: Blackwell.

Willard, A.K., Norenzayan, A. (2013). Cognitive biases explain religious belief, paranormal belief, and belief in life's purpose. *Cognition. 129(2):* 379-391. doi: 10.1016/j.cognition.2013.07.016

Wilson, J.A. (2018). Reducing pseudoscientific and paranormal beliefs in university students through a course in science and critical thinking. *Science & Education*. *27(1-2)*: 183-210. doi: 10.1007/s11191-018-9956-0.

Woodward, J. (2017). Scientific Explanation. In: Zalta, E. N. (ed.). *The Stanford encyclopedia of philosophy* URL = <https://plato.stanford.edu/archives/fall2017/entries/scientific-explanation/>.

Wynn, L.L., Foster, A.M., & Trussell, J. (2009). Can I get pregnant from oral sex? Sexual health misconceptions in e-mails to a reproductive health website. *Contraception*. *79(2)*: 91-97.

Zohar, A., Weinberger, Y., & Tamir, P. (1994). The effect of the biology critical thinking project on the development of critical thinking. *Journal of Research in Science Teaching*. *31(1)*: 183-196. doi: 10.1002/tea.3660310208.