The Interaction of Ignorance and Science: Beyond Simple Opposition. A Review of the Evidence

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Abstract

The common picture places science and ignorance at opposite ends of a line: wherever science advances, ignorance retreats. Research over the past century has questioned this picture. This article reviews examples from the history of science and from several disciplines to ask whether ignorance is always the enemy of science. Its guiding question is what decides whether ignorance helps or harms: who sees it, and whether anyone has chosen or kept it.

Part 1 reviews five possible roles of ignorance in the progress of science: criticising the limits of inherited knowledge, specifying ignorance precisely, tolerating ambiguity, turning ignorance into questions, and the view of people who approach a problem from outside the field or from a distance in expertise.

Part 2 shows that statistics, psychology, neuroscience, sociology, economics and scientometrics have each made one aspect of ignorance measurable or testable, although each discipline calls something different "ignorance".

Part 3 examines four topics in which ignorance harms science: undone science, manufactured doubt, the lack of transparency about the validity of published claims, and the accumulation of literature. The examples suggest that the effect of ignorance depends mainly on two things: who sees it, and whether anyone has chosen or kept it. Ignorance that its owner has seen and turned into a question sometimes leads to progress. But being seen is not enough (undone science is seen, and it still does harm). Chosen ignorance can benefit the person who chooses it, even when it harms others or public trust in science. The aim of this article is to sum up these examples, not to state a proven law. It does not weigh the benefits against the harms, and several questions remain open.

Keywords: ignorance, science, specified ignorance, manufactured ignorance, reproducibility, ignorance studies

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Introduction and Background

A common picture places science and ignorance at opposite ends of a line. On this view, wherever science advances, ignorance retreats, and the two are enemies. Ignorance is nothing more than "not knowing": a gap that experiment and argument will eventually fill. Robert Proctor describes this view as one form of ignorance: a native state that people must overcome and, in the modern age, a void that science hurries to fill (Proctor, 2008, pp. 3–4).

This picture has deep roots. At least in the Greek, Buddhist, Hindu and Hebrew traditions, thinkers set ignorance against knowledge, sometimes as darkness against light.

In the allegory of the cave, Plato describes prisoners who have been chained in a cave since childhood and see nothing but shadows. He defines education as the turning of the soul from what is always changing towards what is lasting and true (Plato, n.d.-b, Republic, Book VII).

In Buddhism, ignorance (avijjā in Pali, avidyā in Sanskrit) is the first link in the twelve-link chain of dependent origination. Each link is the condition for the next, and the chain ends in suffering. Release from suffering depends on removing this ignorance (Britannica, n.d.-a).

Advaita Vedanta, in Shankara's account, follows the same pattern. Ignorance (avidya) makes us see the world as a plurality of separate things. Only the realisation that the self is one with Brahman (ultimate reality) removes it, and this leads to liberation (moksha) (Britannica, n.d.-b).

In the Hebrew tradition, Ecclesiastes says that wisdom excels folly as far as light excels darkness (Ecclesiastes 2:13).

These examples concern "knowledge", "wisdom" and ignorance in their broad, traditional senses (on a generous reading, this includes the "folly" of Ecclesiastes). They do not concern empirical science. We can regard empirical science as a modern form of the search for wisdom, and it is the subject of this article, not knowledge in the general sense.

If the opposition between knowledge and ignorance has a long history, so does doubt about that opposition, and each example below questions one aspect of it.

In the Apology, Socrates says of a man who claims to be wise that "he knows nothing, and thinks that he knows". He describes himself as someone who "neither knows nor thinks that he knows" (Plato, n.d.-a, Apology, 21d). So he counts awareness of his own ignorance as an advantage.

In the same book of the Bible, the unconditional value of knowledge is also doubted: "with much wisdom comes much sorrow; the more knowledge, the more grief" (Ecclesiastes 1:18, NIV).

In 1440 Nicholas of Cusa wrote On Learned Ignorance (De docta ignorantia). In it he treated awareness of the limits of knowing as itself a form of wisdom (Internet Encyclopedia of Philosophy, n.d.).

Montaigne, too, in the "Apology for Raymond Sebond" (Essais, Book II, chapter 12; first published 1580), summed up his scepticism in the motto Que sçais-je? ("What do I know?") (Montaigne, 1580, II.12; Cambridge University Library, n.d.).

The belief that ignorance is simply the absence of knowledge still has defenders in philosophy today. For example, Le Morvan defends the standard view that ignorance is the absence of knowledge (Le Morvan, 2011).

But according to Peter Wehling, a sociologist and theorist of science and technology (Wehling, 2021), this old picture has been challenged for about a century. He regards Ludwik Fleck as the first to look for the source of ignorance in science in the way science itself works. A scientific community, with its own "thought style", notices the facts that fit that style and fails to see those that do not (Fleck, 1935, cited in Wehling, 2021).

Karl Popper, too, begins his 1960 lecture with the objection that ignorance is something negative, the absence of knowledge, so how can it have sources? But he uses this objection to pose his question, and he arrives at what he calls the "conspiracy theory of ignorance": the belief that ignorance may be the work of powers that want to keep us ignorant. Popper calls it a curious

consequence of the belief that truth is manifest. He says that in the main it is a myth, although he sees a grain of truth in it (Popper, 1966, pp. 169, 175–176).

In 1987 Robert Merton introduced the concept of "specified ignorance" as part of the work of science (Merton, 1987, cited in Wehling, 2021).

In the same field, Smithson (1985) described ignorance as "socially constructed". In 2008 Proctor and Schiebinger popularised the word "agnotology", which turned the study of the cultural production of ignorance into an independent field (Proctor & Schiebinger, 2008).

Finally, in 2015, Gross and McGoey wrote in the Routledge International Handbook of Ignorance Studies that ignorance, once seen as simply the absence of knowledge, has become a highly influential subject (Gross & McGoey, 2015).

So we can say that in recent decades the view of the relation between science and knowledge, on the one hand, and ignorance, on the other, has changed. Without judging whether either view is right or wrong, this article tests that relation against the evidence. It neither takes the picture of opposition for granted, nor assumes its reverse, that ignorance assists and strengthens science.

The word "ignorance" has more than one meaning in this article. As a guide to reading (and not as a new classification), we distinguish three states that the researchers named above have used:

• Simple not knowing: the absence of knowledge about something.

• Seen not knowing: awareness of what we do not know (Merton's "specified ignorance").

• Hidden or manufactured not knowing: ignorance that its owner does not see, or that others deliberately create and maintain.

"Being seen" is always relative: we must ask for whom it is seen. The tobacco industry saw the doubt, and the public did not. We note this relativity in each example.

We must also explain that all direct quotations come from English translations, not from the original languages (Greek, Hebrew, Sanskrit and Pali), except Montaigne's French phrase. Where a statement is the author's reading and not the source's claim, we mark it with the phrase "in the view of this article".

The article has the following parts:

• Part 1 examines the senses in which ignorance may have helped the progress of science.

• Part 2 examines how science has supplied tools for understanding and measuring ignorance.

• Part 3 turns to the harmful consequences of ignorance for science today, and for public trust in science and its social use.

• Part 4 deals with open questions.

The Conclusion and the References follow.

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1. How Ignorance Has Helped the Progress of Science

The Introduction showed that the picture of opposition between science and ignorance has been challenged for about a century. This part is the first test of that challenge against the evidence. Instead of being only an obstacle, in what senses can ignorance contribute to the progress of

science? The aim is not to prove that ignorance caused modern science to arise. It is to show the possible roles that ignorance can play.

We review five cases in turn: criticising the limits of inherited knowledge, specifying ignorance precisely, tolerating ambiguity, turning ignorance into questions, and the view of those who approach a problem from outside the field or from a distance in expertise.

In subsections 1.3 and 1.4 the examples are the views of thinkers, not historical or empirical evidence. In 1.6 we set out the limits of each case.

1.1. The Limits of Inherited Knowledge

Knowledge inherited from earlier generations left no room for questions as long as people thought it complete and secure. This subsection reviews examples in which scholars saw the "limits of this knowledge": the places where the answers of earlier authorities were incomplete or wrong. In the view of this article, seeing these limits is one of the ways in which ignorance enters the work of science. What looked "known" yesterday becomes an open question. Let us now look at some historical examples of this view.

In the tenth century, in his Doubts about Galen, al-Razi tested his clinical observations against Galen's teaching. Among other things, he reports that about 300 of 2,000 patients did not do as expected. Pormann describes him as a "critic of authority" who wanted to test medical teaching against "experience", and says that Razi knew the limits of medical knowledge: because medicine deals with particulars, it can reach only "approximate truth values" (Pormann, 2015).

Between 1028 and 1038 CE, Ibn al-Haytham wrote Doubts about Ptolemy (Ptolemaeus Arabus et Latinus, n.d.). According to Langermann, it is a comprehensive critique of Ptolemy's Almagest, Planetary Hypotheses and Optics. It shows where Ptolemy departed from principles such as uniform circular motion around a fixed centre (Langermann, 2007).

In 1543, in On the Fabric of the Human Body (De humani corporis fabrica), Vesalius revised Galenic anatomy systematically, although he never broke with Galen completely (Porter, 2001).

In all three cases, criticism of earlier authorities, that is, showing where accepted knowledge was incomplete or wrong, turned the gaps into research questions.

Nicholas of Cusa finished On Learned Ignorance in 1440. According to the Internet Encyclopedia of Philosophy, he understands "learned ignorance" as a state in which no higher knowledge is attainable. According to the same entry, his argument starts from human desire: since this desire is not in vain in us, we surely want to know what we do not know. This idea is theological. Here we take it as a sign that the intellectual culture of the period acknowledged a limit to knowing, not as a theory of scientific method.

In 1620, in Novum Organum, Francis Bacon listed four kinds of "idols" that keep the mind from the right path. The idols of the tribe have their root in human nature and in the human race. The idols of the cave belong to each individual. The idols of the marketplace arise from people's dealings with one another. The idols of the theatre come from accepted philosophical systems, and Bacon compares them to plays that have been staged (Bacon, 1620, aphorisms 41–44).

In the view of this article, the idols are hidden ignorance dressed as knowledge: places where the mind thinks it knows and does not. Bacon saw the idols as obstacles to inquiry. Recognising them means recognising one's own ignorance, which is a precondition of intellectual progress.

The Royal Society of London held its first meeting on 28 November 1660 at Gresham College. Its motto is Nullius in verba (literally, "on the word of no one"). The Society explains it as "take nobody's word for it", and as an expression of the members' resolve to "withstand the domination of authority", so that they could verify statements by appeal to facts established by experiment (Royal Society, n.d.). In the view of this article, the motto shows the same logic: a claim received from authorities does not count as knowledge until it has been tested.

Yuval Noah Harari, in Sapiens, calls the scientific revolution "a revolution of ignorance". He writes that the great discovery that began it was that humans do not know the answers to their most important questions. In his view, before that, people believed they already had the answers to important questions in sacred texts and in the teachings of their predecessors (Harari, 2014, ch. 14).

Of course, these examples do not claim that modern science is solely the product of criticism of earlier knowledge or of an admission of ignorance, or that there is a causal relation between the two. They show only that, from at least the tenth to the seventeenth century, acknowledging the limits of inherited knowledge and criticising authority were part of the intellectual conversation in different traditions and institutions. They do not prove a unified, worldwide historical trend.

1.2. Specifying the Unknown

In a 1987 article, Robert Merton defined the concept of "specified ignorance" as follows: the explicit recognition of what is not yet known but needs to be known in order to lay the foundations of knowledge (Merton, 1987, p. 7, cited in Wehling, 2021). He called this "problem-finding as a prelude to problem-solving" (Merton, 1987, p. 10, cited in Wehling, 2021). According to Wehling, Merton first raised the concept "more or less incidentally" in the 1950s and developed it in 1987. Wehling reports that Merton wrote that a person's total manifest ignorance grows together with his total manifest knowledge (Merton, 1987, p. 7, cited in Wehling, 2021).

A classic example is Mendeleev's table. In 1869 Mendeleev published his first paper on the periodic table (Purdue University, n.d.). He left gaps for undiscovered elements, predicted their basic physical and chemical properties, and provisionally named three of them "eka-aluminium", "eka-boron" and "eka-silicon" (Kak, 2004). A few years later, Lecoq de Boisbaudran discovered gallium (1875), Nilson discovered scandium (1879) and Winkler discovered germanium (1886). These discoveries confirmed Mendeleev's predictions and helped his table gain wide acceptance (Rabinovich, 2007).

In the view of this article, the gap in the table is an example of specified ignorance. Mendeleev did not know what these elements were, but he knew where they belonged in the table and what properties they should have. This made his prediction testable.

Another example is the planet Neptune. In 1845 Urbain Le Verrier began to study the irregular orbit of Uranus, and in 1846 he calculated the position of a hypothetical planet. On 23 September 1846, after a short search, Galle found the planet less than one degree from the position Le Verrier had calculated (Britannica, n.d.-c).

Yet this logic did not always lead to the right answer. Le Verrier explained the anomalous motion of the "perihelion of Mercury" (the point in its orbit closest to the Sun) by assuming an unknown body inside Mercury's orbit. This body was named "Vulcan", and later observations did not confirm it (Britannica, n.d.-d; Pogossian, 2022). The answer came from elsewhere in November 1915: Einstein's general theory of relativity explained the motion of Mercury's perihelion without assuming Vulcan (Weinstein, 2022).

This example reminds us that, in many cases, specifying a gap does not determine its answer, and sometimes filling the gap requires "changing the theory itself". If we credit every discovery to the "help of ignorance", the claim becomes unfalsifiable. The Vulcan case showed that specified ignorance can also lead to a wrong answer.

According to Wehling, Merton says that specified ignorance does not become obvious at once, and that identifying it requires "conscious theoretical reflection and skill" (Merton, 1987, p. 6, cited in Wehling, 2021). Different theoretical perspectives also specify different kinds of ignorance (Merton, 1987, pp. 8–10, cited in Wehling, 2021). Wehling himself concludes that, because specifying ignorance is inevitably "selective", part of ignorance always remains unspecified. He adds that Merton did not develop this "unspecified ignorance" further (Wehling, 2021, pp. 5–6).

We should also mention Karin Knorr Cetina, who in Epistemic Cultures studies how different sciences work in their laboratories. She speaks of "negative knowledge": knowledge about the "limits of knowing", not about "the absence of knowledge". It concerns the errors we make when we try to know, the factors that get in the way of knowing, and what we are not interested in and do not really want to know (Knorr Cetina, 1999, ch. 3, p. 64). From the viewpoint of everyday laboratory work, this concept comes close to what Merton called "specified ignorance". The two concepts are not the same, however, and this article does not choose between them.

1.3. Tolerating Ambiguity: Keats's "Negative Capability"

In a letter to his brothers George and Tom, dated 21 December 1817, John Keats wrote of "negative capability": the ability to remain in uncertainties, mysteries and doubts, without an impatient reaching after fact and reason.

He gives Coleridge (Samuel Taylor Coleridge, 1772–1834, English Romantic poet and critic) as an example of someone who lacks this ability. Coleridge would let go a fine, isolated semblance of truth, taken from the innermost shrine of mystery, because he cannot rest content with "half-knowledge" (Keats, 1817). Of course, this remark concerns poetry, and applying it to science is an analogy. We cite it here because it can be compared with Merton's view.

The physicist Richard Feynman expresses a similar view from inside science in his 1955 lecture on "The Value of Science". A scientist who does not know the answer to a problem is ignorant, and to progress he must recognise this ignorance and leave room for doubt (Feynman, 1955). These two views, together with the view of Merton, who writes of making precise what we do not know, give three approaches to one problem: not hurrying to answer (Keats), recognising ignorance (Feynman) and delimiting it (Merton).

1.4. Questions before Answers

Stuart Firestein, a neuroscientist, calls ignorance the "engine of science" in his book Ignorance: How It Drives Science (Firestein, 2012). According to Michael Shermer's review, Firestein says that ignorance is the engine of science because it is almost unlimited. He advises scientists to forget the answers and work on the questions (Shermer, 2012). In a 2012 interview, Firestein says that what is not known is far greater than what is known, and that when scientists talk to one another they talk about what they do not know (O'Brian, 2012).

Proctor, too, in his account of the first form of ignorance (the "native state"), writes that ignorance is necessary to keep the wheels of science turning. New ignorance must be gathered constantly to satisfy the insatiable appetite of science (Proctor, 2008, p. 5). These views show that this outlook is also present among scientists themselves and among researchers of ignorance.

1.5. Newcomers and Disciplinary Distance

In The Structure of Scientific Revolutions, Thomas Kuhn reports a historical observation: almost always, the people who achieved the fundamental inventions of a new paradigm were either very young or very new to the field (Kuhn, 1962, ch. 8, p. 90). Of course, this is a narrative observation, not a statistical measurement, and youth or being a newcomer is not the same as "ignorance".

This observation matters for our discussion because a newcomer lacks at least part of the knowledge and customs of a field. So we can ask whether this lack has sometimes helped the work of science. We test the question against later studies, and for each we ask whether what was measured is really ignorance or something else.

In 2008 Bilalić, McLeod and Gobet studied a "chess problem" (a position on the board in which the player must find the best move). They showed that seeing a familiar solution triggers the Einstellung effect (the tendency to stick to the familiar solution and miss a better one), even in experts (Bilalić et al., 2008a).

Another paper by the same group, however, concluded that the inflexibility of experts is both reality and myth. Experts also showed the effect and sometimes failed to find the better solution despite the familiar one, but the higher the level of expertise, the less they were affected (Bilalić et al., 2008b).

In a 2010 study, Jeppesen and Lakhani examined 166 scientific problems that more than 12,000 scientists had tried to solve. The greater the distance between the solver's field of expertise and the field of the problem, the greater the chance of providing the winning solution. Technical and social "marginality" also played a role in individual success (Jeppesen & Lakhani, 2010).

Against this finding, Benjamin Jones's "burden of knowledge" model predicts that, as knowledge accumulates, the level of education, specialisation and teamwork will rise over time (Jones, 2009).

Another piece of evidence from the economics of science concerns the same boundary between disciplinary distance and ignorance. Azoulay, Fons-Rosen and Graff Zivin reported that after the early death of an eminent life scientist, the flow of papers by his collaborators in the field falls, and the flow of papers by non-collaborators rises sharply. The papers of these newcomers draw on a different body of scientific literature and are cited more. According to the authors, while the scientist is alive, newcomers seem less willing to challenge the leaders of the field (Azoulay et al., 2019).

Of course, what was measured is the entry of non-collaborators and the frequency of citation, not ignorance. So this finding too is mainly about disciplinary distance and the structure of influence in a field, and it has been reported only for the life sciences.

But a more important question here is whether these studies are really talking about "ignorance". In fact, what Jeppesen and Lakhani measured is the distance between the solver's field of expertise and the field of the problem, not the absence of knowledge. To link this with ignorance, we would have to define precisely the amount of "knowing" and "not knowing" about the new field, and the distance between the fields, in the form of an intellectual project, which is not easy. We must keep this in mind so that we do not read more into the evidence than it can bear.

1.6. The Limits of These Examples

The examples above show possible roles of ignorance, but they have five limits.

First, a theory revealed the gap (the periodic law for Mendeleev and Newtonian mechanics for Le Verrier). So what proved useful was not raw ignorance but knowledge about the limits of knowing. We should credit the benefit to ignorance that has become a question, not to every kind of ignorance.

Second, the ignorance that proved useful was named, or at least delimited, and, according to Wehling, Merton makes recognising it depend on theoretical knowledge and skill.

Third, specifying a gap does not guarantee the right answer, as the Vulcan case shows.

Fourth, "ignorance is the engine of science" is a metaphor that Firestein himself uses, and it does not show that every ignorance turns into a useful question.

Fifth, being a newcomer or an outsider is not always useful. In the study by Bilalić and colleagues (Bilalić et al., 2008b) we saw that the higher the expertise, the less the inflexibility. In Jones's model, the accumulation of knowledge means more education before a person reaches the edge of knowledge.

Beyond all this, we must also bear in mind the great difficulty of treating being a newcomer, or distance from the field, as equivalent to "being ignorant".

So this part shows only one thing: ignorance helps the work of science when someone has seen it and turned it into a question. In the later parts we shall see that "being seen" is not enough, and that who sees the ignorance, and whether anyone has chosen or kept it, matter just as much.

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2. How Science Has Helped Us Understand Ignorance

This part continues Part 1. There we saw how ignorance can help the progress of science. Here we ask what science has told us about ignorance itself, and how it has helped our understanding of the concept. We must note at once that the word "ignorance" does not have a single meaning in these fields. Sometimes it is uncertainty, sometimes not knowing what one does not know, sometimes avoidance of knowing. This article does not choose between these meanings.

It seems that, over the last century, at least six fields of research have each examined one aspect of ignorance:

• Statistics and information theory made one part of it, uncertainty, measurable.

• Psychology asked how far the owner of ignorance sees it.

• Neuroscience examined how the brain deals with missing information: with ambiguity, with the assessment of its own knowledge, and with curiosity.

• Sociology examined the function and the social construction of ignorance.

• Economics examined its deliberate choice.

• Scientometrics counted the volume of the scientific literature, the setting in which researchers' ignorance forms.

Let us look at each more closely.

2.1. Statistics and Information Theory: Risk and Uncertainty

In 1921, in Risk, Uncertainty and Profit, Frank Knight distinguished two kinds of "not knowing the future". In his view, in "risk" we do not know the outcome of each event, but we do know in

what proportions the outcomes would occur if a similar situation were repeated many times. That proportion is known either by calculation (as with the throw of a die) or from the statistics of experience (as with the rate of house fires for an insurance company). In "uncertainty" the situation is so unique that we have no group of similar cases from which to take this proportion, as when someone starts an entirely new business. So Knight kept the word "risk" for measurable unknowability, and "uncertainty" for the unmeasurable kind (Knight, 1921, Part III, ch. VII and the beginning of ch. VIII).

In 1948 Claude Shannon introduced a quantity called H, which measures how much "choice" is involved in selecting an event, or how uncertain we are about the outcome. He showed that expressions of this type have "a central role in information theory as measures of information, choice and uncertainty" (Shannon, 1948, section 6).

In the view of this article, and in Knight's terms, a quantity defined on a known probability distribution measures "risk", not "uncertainty". So information measures, although precise, cover only part of ignorance: the part whose distribution is known.

In engineering, Der Kiureghian and Ditlevsen divided uncertainty into two types: "epistemic", which the modeller sees as reducible, and "aleatory", which the modeller does not expect to be reducible. In their words, this distinction is useful in practice because it shows which uncertainties can be reduced (Der Kiureghian & Ditlevsen, 2009). It seems, however, that this definition depends on the modeller's viewpoint. Whether an uncertainty counts as epistemic or aleatory depends on whether the modeller thinks it can be reduced, not necessarily on the nature of the phenomenon.

Van der Bles and colleagues, in their review, offered a framework for communicating uncertainty to a general audience. It has three subjects (facts, numbers, science) and two levels: direct (explicit expression) and indirect (expression through the quality of the evidence). They reported that "some evidence" suggests that expressing uncertainty does not necessarily harm the audience, although effects depend on the individual and on the format of the message (van der Bles et al., 2019).

To see the place of these tools in the larger picture of ignorance, we turn to Smithson's taxonomy. He places uncertainty (which includes probability, ambiguity and vagueness) as a subset of "error", and places taboo, untopicality and undecidability under "irrelevance" (Smithson, 2022). In Smithson's own terms, "error" is the passive side of ignorance and "irrelevance" is its active side.

Note that Smithson uses the word "uncertainty" more broadly than Knight. Probability, which Knight called measurable "risk", falls itself under "uncertainty" in Smithson's taxonomy. From here on, wherever we speak of uncertainty without qualification, we mean this broader sense, not Knight's.

In the view of this article, what the research above measures or models falls on the "error" side of this taxonomy and is part of ignorance, not all of it. The active side, that is, ignorance maintained by taboo or by deeming something unimportant, is not measured by these tools.

2.2. Psychology: Unseen Ignorance and Selective Ignorance

In 1999, in four studies, Kruger and Dunning reported that participants in the bottom quartile on tests of humour, grammar and logic greatly overestimated their performance. Their scores put them at the 12th percentile, and they estimated themselves at about the 62nd. The authors linked this mismatch to weak "metacognition", that is, "the ability to distinguish accurate from inaccurate judgements" (Kruger & Dunning, 1999). The interpretation of this pattern is disputed (Krueger &

Mueller, 2002; Gignac & Zajenkowski, 2020; Dunkel et al., 2023), but it matters for our discussion in two ways.

First, science has been able to turn the question "does a person who does not know something see that he does not know it?" into a testable question. This is itself an example of the "turning of ignorance into a question" that we saw in Part 1.

Second, if the Kruger–Dunning pattern (as reported) is correct, then ignorance sometimes stays hidden from its owner, and in that case it cannot turn into a question by itself. But since the existence and size of this pattern are debated, we take this only as a possibility, not as a firm finding.

In another psychological study relevant to our discussion, Kahan and colleagues reported that the people with the highest scientific literacy and technical reasoning skill were not the most worried about climate change. At the level of groups, they were the most culturally polarised (Kahan et al., 2012). This finding is relevant to our discussion because it shows that more knowledge and reasoning skill do not by themselves remove disagreement over a scientific issue. So the relation between knowledge and ignorance cannot be explained simply by "the more knowledge grows, the less ignorance there is". This study does not say that these people are ignorant, and we do not judge here the cause of the polarisation.

Mercier and Sperber also argued that the function of reasoning is not to reach the truth but to produce and evaluate arguments in order to persuade. So the tendency towards confirmation that is built into this function can sustain false beliefs. They also say that the same function can lead to better outcomes in group discussion (Mercier & Sperber, 2011).

In the view of this article, if we take "false belief" as an instance of ignorance and "disagreement over a scientific issue" as a sign of not knowing, the work of Mercier and Kahan shows that what is usually called ignorance does not always come from a lack of information. Sometimes it persists even with high knowledge and reasoning skill. We should recall especially that Hertwig and Engel also spoke of "deliberate ignorance" and defined it as the "conscious choice not to seek or use knowledge (or information)" (Hertwig & Engel, 2016).

Hertwig and Engel also believe that psychologists have so far paid relatively little attention to the study of ignorance, let alone its deliberate kind (Hertwig & Engel, 2016). This suggests that the contribution of psychology to our understanding of ignorance, for all the examples above, is still limited.

2.3. Neuroscience: Ambiguity, Metacognition and Curiosity

Neuroscience has not made ignorance its direct subject. What it has studied are the nearest consequences of ignorance. We give three examples.

Ambiguity. Hsu and colleagues, in a paper in Science, studied the brain during decision-making under "ambiguity", that is, when information about probabilities is incomplete. They reported that activity in the amygdala and the orbitofrontal cortex correlates positively with the degree of ambiguity, while the striatum shows the reverse pattern. The choices of patients with orbitofrontal damage did not change as ambiguity increased (Hsu et al., 2005).

Awareness of one's own knowledge. Fleming and colleagues reported that people's introspective accuracy about whether their perceptual decisions were correct is related to the grey-matter volume of part of the right prefrontal cortex (Brodmann area 10) (Fleming et al., 2010). This study connects

with the psychological question of the previous section: the ability to see the limits of one's own knowledge can be measured and has a basis in the brain.

Curiosity. Kang and colleagues measured epistemic curiosity with general-knowledge questions. They reported that it is accompanied by activity in the caudate nucleus, and that memory-related areas are more active when the participant's guess was wrong (Kang et al., 2009).

Gruber and colleagues used brain imaging (fMRI) to show that participants remembered material they had seen in a state of high curiosity better, and that activity in the midbrain and the nucleus accumbens rose in high curiosity. They concluded that curiosity and extrinsic reward motivation may share neural mechanisms (Gruber et al., 2014). Kidd and Hayden, in a review, defined curiosity as "a motivational state for information". They reported that dopamine cells in monkeys respond, in experiments on resolving uncertainty, to the possibility of early information, and that information is, in their words, an "indirect reward", not a primary one. They write that the biological function and the neural mechanism of curiosity are still not well understood and that there is no consensus on a unified definition (Kidd & Hayden, 2015).

In the same area, Sharot and Sunstein proposed a framework in which people predict what effect information will have on their action, emotion and thinking. From this assessment they build an overall value, which determines whether they seek the information or avoid it (Sharot & Sunstein, 2020).

This article links curiosity to ignorance because curiosity is a response to a "perceived" gap in knowledge. This idea appeared earlier in Loewenstein's information-gap theory, which sees curiosity as arising from the perception of a gap in knowledge or understanding (Loewenstein, 1994). So epistemic curiosity is usually triggered by awareness of not knowing. This link is, of course, one that the neuroscientific studies above do not state themselves. From the same viewpoint, the studies of ambiguity and curiosity also show that, in the conditions studied, not knowing is not a neutral state: it goes with activity in areas linked to emotion and reward. This too is our interpretation, not a direct claim of these studies.

2.4. Sociology: Ignorance as Function and as Construction

This subsection asks what sociology and social studies say about ignorance. We review several examples.

In 1949 Moore and Tumin listed the social functions of ignorance, including:

• "preserving privileged positions", for example the consumer's dependence on the expert and the secrecy of pay;

• "reinforcing traditional values" (ignorance of alternatives and of the cost to the individual of departing from tradition);

• "preserving fair competition";

• "the persistence of stereotypes".

They also believed that awareness of what we do not know can be a motive for research (Moore & Tumin, 1949).

In 1987 Merton developed the concept of "specified ignorance", that is, ignorance that the researcher recognises in the form of a question (Merton, 1987, cited in Wehling, 2021).

Proctor and Schiebinger regarded one form of ignorance as actively made (Proctor & Schiebinger, 2008).

McGoey, in a case study of the licensing of the antibiotic Ketek by the US Food and Drug Administration (FDA), argued that knowledge and ignorance are not opposites. Ignorance can be a resource for individuals and institutions, for example to secure resources, to avoid blame after a crisis, or to claim expertise when there is no certainty. She reports that in that case doctors, regulators and the drug's makers competed with one another in claiming "the least knowledge" about the drug's efficacy and safety. But this report does not allow us to conclude that they knowingly pretended not to know (McGoey, 2012).

In the view of this article, what these studies have in common is that they do not treat ignorance as only the absence of knowledge. In society it sometimes has a function, sometimes takes the form of a question, and sometimes is made or maintained.

Another branch that studies the construction of ignorance comes from philosophy. For example:

Tuana, in a paper on the women's health movement, argues that the systematic study of ignorance should be part of every theory of knowledge. From this viewpoint she lists kinds of ignorance and the ways they are produced, and she regards resistance movements as a suitable place to identify, criticise and transform ignorance (Tuana, 2006).

In the collection by Sullivan and Tuana, this view was extended to race (Sullivan & Tuana, 2007). Mills, in the chapter "White Ignorance", describes an ignorance that is not accidental and in which racism and "white racial domination" play a causal, decisive role (Mills, 2007, p. 20).

Nevertheless, we should remember that these examples are conceptual, historical or case analyses, and their claim is interpretive. We do not set them on a par with the statistical measures of the earlier fields, and we do not generalise them to the natural sciences. The work of Tuana and Mills is also about the social structure of knowledge, and it makes a normative claim as well.

2.5. Economics and Behavioural Economics: Rational Ignorance and Strategic Ignorance

In An Economic Theory of Democracy, Anthony Downs argued that one citizen's vote has almost no chance of deciding an election, while acquiring political information costs time and money. So for many citizens, the rational course is not to invest in political information (Downs, 1957, pp. 245–246).

Economists call this argument "rational ignorance": remaining ignorant when the cost of acquiring information is greater than its expected benefit (Williams, 2021, p. 7807).

Williams calls the ignorance that arises from the cost of acquiring knowledge "acquisitional ignorance", and distinguishes it from "motivated ignorance": keeping away from knowledge whose possession carries an expected cost, such as distress or an unpleasant consequence (Williams, 2021).

In our view, the two studies below are examples of the first type.

In 1961 George Stigler offered a theory of search for information in the market. A buyer searches more if he spends more on the good, if prices differ more among sellers, or if he is a regular customer and not a passing one (Stigler, 1961). That is, he stops searching where the cost of continuing exceeds the benefit, and so he does not know part of the prices (the author's reading).

In 2003 Christopher Sims built a model in which a person takes in only a limited amount of information from the world. He expressed this limit through the concept of "capacity" (channel

capacity) from "Shannon's information theory", that is, the maximum amount of information that a communication channel can carry (Sims, 2003).

The author makes the link between this assumption of the model and ignorance: we can regard "the limit on information-processing capacity" as a form of ignorance.

In contrast, in psychology and economics there is a phenomenon called "information avoidance". It refers to a situation in which the information itself can affect a person's satisfaction or payoff, so the person may avoid it even if it is useful and free and no "strategic consideration" is involved (Golman et al., 2017, p. 96).

Golman, Hagmann and Loewenstein take this concept, in its broad sense, to include "any behavioural or cognitive process" that prevents a person from reaching the conclusion to which an impartial analysis of the information would have led (Golman et al., 2017, p. 99). But for "active information avoidance" they set a narrow, specific definition. The person must know that information is available, and must avoid it while obtaining it is free for him, or would avoid it even if it were free (p. 97).

For example, a person whose medical test result is freely available and who still does not read it has avoided information actively. But a person who does not read it because he must pay for it does not fit this definition, because the reason he does not read is cost, not escape from the information itself. They divide the motives into two kinds:

• "hedonic": avoiding news that makes one feel bad;

• "strategic": avoiding information as a means to some goal, a goal that concerns either the person alone (intrapersonal) or his relations with others (interpersonal) (Golman et al., 2017).

By introducing the concept of "moral wiggle room", Dana and colleagues described how not knowing the consequences of a choice for others can make selfish behaviour possible without damaging the person's moral image (Dana et al., 2007).

Carrillo and Mariotti also built a model in which a person's preferences change over time, and they called these "time-inconsistent preferences": what the person wants now is not what he will want later. An example is someone who wants to eat less today but knows that tomorrow craving will overcome him. Such a person cannot commit himself to his future decisions, and he may abandon learning half-way and act with "self-restricted information". The authors call this "strategic ignorance", and they show that in their model this kind of ignorance is better, in terms of the person's welfare over time, than continuing to learn to the end (Carrillo & Mariotti, 2000).

In our view, the combined result of these studies is that in economic models ignorance is sometimes chosen and can benefit the chooser, though sometimes at the expense of others. That is, it is not always a deficiency.

2.6. Scientometrics: The Volume of the Scientific Literature

Bornmann and Mutz analysed Web of Science data up to 2012 and reported that the cited references in the last phase of growth (of the three phases they identified) grew by about 8 to 9 per cent a year (Bornmann & Mutz, 2015). Nature interpreted this as a doubling of global scientific output "about every nine years" and noted the limits of the study (Van Noorden, 2014). Of course, the number of cited references measures the volume of the literature, not the amount of knowledge. In this part we take it as a proxy for the growth of reported findings: more literature usually means more reported findings, without assuming that those findings are correct. In 3.3 we shall see that the validity of some of them is in question.

2.7. The Limits of These Examples

The examples above give a picture of the contribution of science to understanding ignorance. Before any conclusion, however, we must make clear the limits of their validity. Three warnings are needed.

First, each discipline calls something different "ignorance", or asks about something different: measurable uncertainty, wrong estimation of one's own ability, the response to ambiguity and the motive to seek information, the social function and construction of ignorance, ignorance that arises from the cost of acquiring knowledge or that a person chooses for himself, and the volume of literature the researcher must know. These do not fit one definition, and even in philosophy there is a dispute over whether ignorance is simply the "absence of knowledge". For example, Peels does not regard ignorance as the absence of knowledge (Peels, 2010), but Le Morvan defends the standard view, which does (Le Morvan, 2011). Peels, in reply (Peels, 2011), proposed the absence of true belief. Continuing these disputes, El Kassar has reopened the same question in her study of the foundations of the epistemology of ignorance (El Kassar, 2018).

Second, most of these findings come from controlled experiments, theoretical modelling or case studies, and their generalisation to real life is limited. For example, the researchers themselves say that our knowledge of the neural mechanism of curiosity is still incomplete (Kidd & Hayden, 2015), and in nationally representative data the Kruger–Dunning pattern was very small (Dunkel et al., 2023).

Third, these fields are not themselves immune to error. In Part 3 (3.3) we shall see how psychology has had trouble reproducing its findings.

These warnings do not make the examples in this part worthless. In our view they show that science, by making at least some parts or aspects of the phenomenon of ignorance measurable or testable, has helped our understanding of it, although it does not yet have a unified picture of it.

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3. The Shadow of Ignorance over Science Today

Part 1 spoke mostly of the constructive contribution of ignorance to the progress of science, and Part 2 of the help that science has given to the understanding of ignorance. But this picture has another side: cases in which ignorance has harmed science, and conditions that expose researchers to it. This part reviews four topics on the basis of documented research.

3.1. Undone Science

In 2010 Frickel and colleagues used the term "undone science" for areas of research that matter to social movements and civil groups but that, because of the structure of funding and institutional priorities, are not carried out or remain incomplete (Frickel et al., 2010). In the author's view, this concept shows that not all "scientific ignorance" is a "natural boundary of knowledge". Part of it results from what gets researched and what does not. Even so, we must keep the claim precise. The concept does not by itself say which topics "should" have been researched. Social movements and interested groups decide this, and each case must be judged separately.

A similar gap appears in drug development. Trouiller and colleagues reported that, of 1,393 new chemical entities that reached the market between 1975 and 1999, only 16 were for tropical diseases and tuberculosis. They saw this as the result of a deficient market and a failure of public-health policy (Trouiller et al., 2002). This figure shows a pattern in market and policy priorities, but it says nothing about whether every scientific gap resulted from neglect.

3.2. Manufactured Ignorance in Industry

A well-known, classic example is the tobacco industry. A 1969 document of the Brown & Williamson company, titled "Smoking and Health Proposal", says: "Doubt is our product since it is the best means of competing with the 'body of fact' that exists in the mind of the general public" (cited in Michaels, 2008; Proctor, 2011). But we must remember that this document relates to one company and one period, and by itself it does not pass judgement on the whole industry.

Proctor in Golden Holocaust (Proctor, 2011), and Michaels in Doubt Is Their Product (Michaels, 2008), argue that doubt about scientific evidence was produced deliberately. Oreskes and Conway, in Merchants of Doubt, also argued that the same pattern, and sometimes the same few scientists, recurred in other issues such as acid rain, the ozone layer and climate change (Oreskes & Conway, 2010). This is their argument, and we do not test it here.

McGoey also argued that some institutions likewise use ignorance for "strategic" purposes (McGoey, 2012), as we saw earlier in the Ketek case (2.4).

The other side of the story appears in behavioural economics, where it is said that ordinary people sometimes avoid information (Golman et al., 2017; Hertwig & Engel, 2016).

In another case, Kahan and colleagues also showed that greater scientific literacy does not necessarily reduce disagreement, and that on climate change the cultural groups with higher literacy were more polarised (Kahan et al., 2012).

In the view of this article, perhaps manufactured doubt does not depend only on "supply" but also rests on a background of "psychological demand". This is a guess that comes from putting these studies side by side, not a claim of the studies themselves.

3.3. Ignorance within Knowledge Itself: Reproducibility and Thought Style

In 2005, in a theoretical model, Ioannidis argued that under many conditions most published research findings may be false, for structural reasons such as small samples, analytical flexibility and publication bias (Ioannidis, 2005). In 2015 the Open Science Collaboration repeated 100 psychology experiments. Ninety-seven per cent of the original studies had reached a statistically significant result (that is, they judged the reported effect to be far from chance), but only 36 per cent of the replications did so (Open Science Collaboration, 2015).

In the author's view, a failed replication does not prove that the original study was wrong, and the results of this collaboration measure only psychology and should not be generalised to all the sciences.

There is evidence from biomedicine too. Begley and Ellis, in a note in Nature, reported that researchers in haematology and oncology at the company Amgen could confirm the findings in only 6 (11 per cent) of 53 landmark studies in cancer research (Begley & Ellis, 2012).

Here too, the researchers note that they deliberately chose papers that reported something entirely new, and that technical differences may also have played a part in the failed confirmations. So this figure does not represent all cancer research.

In the view of this article, the important point is that the published literature contains claims whose real status we do not know. This is ignorance about "the validity of what is known", not about "open questions". Ignorance sometimes sits inside knowledge itself, not outside its boundaries.

In the same vein, Fleck showed from another angle that ignorance can stay hidden inside science. A scientific community, with its own "thought style", notices the facts that fit that style and fails to see those that do not (Fleck, 1935, cited in Wehling, 2021).

Kuhn also writes that normal science often suppresses fundamental novelties because they inevitably call into question the foundations of its own commitments (Kuhn, 1962, ch. 1). In this case, the ignorance is not seen from the viewpoint of the scientific community itself.

Of course, these are theories about how science works, not statistical measurements. So we say only that such ignorance is possible, and we do not say how common it is.

3.4. The Accumulation of Scientific Literature

In 2.6 we saw that cited references in the last period of growth have been growing by about 8 to 9 per cent a year, and we took this as a measure of the volume of the literature, not of knowledge. In a theoretical model, Jones argued that, as knowledge accumulates, the "burden of knowledge" increases. Innovators spend more time reaching the frontier of knowledge, their expertise becomes narrower, and teams grow larger (Jones, 2009).

This research and the growth of the literature together show that each researcher must know a smaller part of the literature of his field, and that narrower expertise means more ignorance about what lies outside it. Of course, this is our reading. Jones does not speak of ignorance, and we do not say that this ignorance disrupts the whole progress of science.

These four topics show other faces of ignorance. They show that:

• sometimes ignorance results from selection: what gets researched and what does not;

• sometimes it is made deliberately;

• sometimes it sits inside the published literature itself, because the validity of part of the claims is unclear;

• and sometimes it arises from scale: the more the literature grows, the smaller the part of it that each researcher knows.

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4. Open Questions

The review above raises several questions, which we take up in this part.

First, the relative weight of ignorance in the progress of science and in its harm. This article has given examples from both sides of the mutual interaction of ignorance and knowledge, but it does not show which side is heavier overall. Answering this question requires a comparative design and data that we have not seen so far.

Second, the measurability of specified ignorance. If a researcher states explicitly what he does not know, can we trace this in the scientific literature and see whether it relates to later outcomes, for example new questions or citations?

Third, ignorance about the validity of what is known. How can the validity status of published claims be made clear to researchers and readers, without making the literature even heavier?

Fourth, individual and collective ignorance. If the growth of the literature forces each researcher to know a smaller part of it, what mechanisms (reviews, teams, groups) fill this gap, and at what cost?

Fifth, a common language. Each discipline uses the word "ignorance" in its own sense. Can we find, without building a new classification, a common language for interdisciplinary discussion?

Sixth, trust in experts. If no expert can know all aspects of a social problem, on what basis can ordinary people trust the advice of experts, and how can this trust stay in proportion to the real validity of their claims?

Seventh, justified doubt and manufactured doubt. Consider the findings of Kahan and colleagues, rational ignorance, undone science, and the role of interests at the different stages of research (from the choice of topic to the drawing of conclusions). In view of these, how can we tell justified doubt about research from manufactured doubt?

This article has no answer to these questions.

Conclusion

This article asked what the relation between science and ignorance is, without accepting in advance either their opposition or its reverse.

In Part 1 we saw that ignorance can serve the work of science in several senses. A researcher may see the limits of inherited knowledge, specify precisely what he does not know, tolerate ambiguity, turn ignorance into a question, or look at a problem from outside the field or from a distance in expertise. These are possible roles, not proof that science was born of ignorance. In our examples, too, what proved useful was not raw ignorance. It was ignorance that someone had seen and delimited, and often a theory had revealed the gap.

In Part 2 we saw that science, from statistics to scientometrics, has made parts of ignorance measurable or testable. But each discipline calls something different "ignorance", and precise tools cover only part of it.

In Part 3 we saw that ignorance sometimes harms science and trust in it: when something is not researched, when doubt is deliberately manufactured, when the validity of some published claims is unclear, and when the growth of the literature forces each researcher to know a smaller part of it.

From this evidence, the article draws three conclusions.

First, science and ignorance are not simple opposites: wherever science advances, ignorance does not necessarily retreat.

Second, the reverse of this picture, that we should count ignorance as the engine of science, is not so simply acceptable either. The ignorance that proved useful was mostly specified and testable, and specifying a gap does not guarantee the right answer, as the Vulcan case showed.

Third, "being seen" is not enough by itself as a criterion. Undone science and the neglect of tropical diseases were seen, and they still harmed science and people. Manufactured doubt was seen by its makers and hidden from the public. In economics, chosen ignorance sometimes benefits the person who chooses it, though it may harm others.

The aim here is to sum up these examples, not to state a proven law, and the pattern has exceptions. How the benefits and harms weigh overall is a question that this review does not answer. We have left it open, with six other questions, in Part 4.

Ignorance is neither the enemy of science nor its mother. Its role in relation to science depends on whether it is recognised or stays hidden. We need to find out where ignorance has been seen and where it has stayed hidden, who sees it, and whether anyone has chosen or kept it.

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