Our students learn science in school, but are we teaching them how to identify scientific misinformation?

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By hindering our ability to mount a swift and unified response to the challenges humanity is faced with, scientific misinformation poses an existential threat to our lives and civilization. To exemplify the detrimental effect of scientific misinformation on our collective response to current global challenges, the first section of this article discusses the impact of vaccine hesitancy and climate change denialism. This is followed by an evaluation of how critical aspects of the scientific method and the skills required to gauge the reliability of scientific sources are implemented in school curricula at the primary and secondary levels. The final section builds upon the previous two to provide suggestions on strategies to empower future generations with the scientific literacy and critical thinking skills required to rise up to the challenges they will undoubtedly be faced with.

Science literacy is a matter of life or death – literally

Only a few years ago, the word 'scientist' would have conjured up for most people mental images of lab coat-clad, scruffy-haired brainiacs chalking incomprehensible equations in their ivory tower. Science and scientists have increasingly crossed the boundaries of labs and universities and have now become commonplace in our evening newscasts and everyday conversations. No period in human history has seen a greater popularization of the scientific discourse than the last decade, from the daily updates on *R* values and viral variants at the peak of the COVID-19 pandemic to reports of ever-more-frequent heatwaves and anomalous weather events brought about by climate change. As humanity faces global threats of unprecedented magnitude, governments and people worldwide turn to scientists for solutions. Paradoxically, it is increasingly frequent for expert advice to be ignored or actively opposed by large swathes of the public, often with the support of prominent political figures. After all – to use the words of an influential British politician – "the people of this country have had enough of experts […] saying that they know what is best". To fully appreciate the extent of the existential threat posed by scientific misinformation, there are perhaps no better examples than vaccine hesitancy and climate change denialism, which will be discussed in the following section.

Prior to the onset of the COVID-19 pandemic, several countries experienced the re-emergence of measles outbreaks in communities where vaccine coverage fell below the herd immunity threshold, allowing the virus to quickly spread within the population. Substantial evidence indicates that the decline in measles immunization was linked to claims (widely disproved by scientific evidence) that the MMR (measles, mumps, rubella) vaccine is associated with developmental disorders and autism in children. More recently, the development of safe and effective vaccines against SARS-CoV-2 within months of the start of the pandemic has been widely recognized as an unprecedented global healthcare success story (effectively summarized in graphical format by Mallapaty and colleagues in a recent *Nature* article, available in 'Further reading'). COVID-19 immunization campaigns have greatly reduced hospitalizations and mortality associated with the virus, allowing many countries to lift restrictive measures and restore a sense of normality. However, COVID-19 vaccines have been met with controversy and open hostility even before they had been developed and administered. Having found fertile ground among populations disillusioned by socio-economic uncertainty and stoked by populist political manoeuvring, anti-vaccination movements have fiercely voiced their distrust of the medical and scientific establishment. While vaccine hesitancy and refusal can be traced as far back as the practice of vaccination itself, their impact has been greatly amplified by the widespread access to social media and online 'echo chambers' where anti-scientific views and conspiracy theories are shared without any fact-checking or verification. It would be tempting to brush off anti-vax views as legitimate (albeit misinformed) expressions of free speech and bodily autonomy. However, particularly when it comes to transmissible diseases, an individual's words and actions can have a dramatic detrimental impact on the health and life of others and of the wider society – even more so as citizens of a globalized civilization.

As many countries start to slowly recover from the impact of the pandemic, the world is still facing a crisis of catastrophic proportions: anthropogenic climate change is a dramatic example of how unregulated human activity and scientific misinformation can pose a global threat to humanity and the wider biosphere. Former US president Donald Trump vocally denied the existence of anthropogenic climate change, publicly referring to it as a 'hoax' orchestrated by the Chinese government to weaken the US economy. Under Trump's administration, the USA – one of the world's largest greenhouse gas emitters – officially withdrew from the Paris climate agreement in 2020. The Paris agreement, signed in 2015 by 196 countries, endeavours to cut global greenhouse gases emissions with the aim to keep the global temperature increase below 2°C (though preferably below 1.5°C) compared to pre-industrial levels. In 2018, the Intergovernmental Panel on Climate Change (IPCC) reported that even a 'best case scenario' increase of 1.5°C would have a catastrophic impact on our biosphere (see 'Further reading'). The IPCC report findings were further consolidated by a study recently published by McKay and colleagues in *Science*, highlighting that a temperature increase between 1.5 and 2°C could lead to 'tipping points' for multiple critical systems – including the Greenland and west Antarctic ice sheets, low-latitude coral reefs and permafrost – leading to positive feedback loops with irreversible and unpredictably dire consequences. It is vital that the global community remains committed to the Paris agreement in the endeavour to find sustainable alternatives to fossil fuels, minimize the emission of greenhouse gases and limit the anthropogenic temperature increase as a matter of urgency. Attempts by policy makers and non-governmental organizations to highlight the dangers of climate change and take action against it have been thwarted by disinformation campaigns downplaying the impact of human emissions on global warming. It has been estimated that, over the last decades, world-leading fossil fuel corporations spent hundreds of millions of dollars lobbying to mislead the public and block or delay the implementation of carbon-reduction policies. Recently, a US House panel called the leaders of major fossil fuel companies to testify at a hearing to 'get to the bottom of how fossil fuel companies have raked in trillions of dollars of profit at the expense of our planet and our health, all while spreading doubt and disinformation about the dangers of fossil fuels'. The vested interest of fossil fuel corporations' in maintaining the status quo, the polarization of the political discourse and the lack of fact-checking in online fora have combined to form the perfect storm for the uncontrolled diffusion of climate science misinformation. The World Health Organization estimates that climate change is predicted to result in 250,000 additional deaths globally every year between 2030 and 2050. However, unlike COVID-19, it is unlikely that climate change will be mentioned in the death certificates of its victims. Like vaccine hesitancy (and arguably to an even greater extent), climate change denialism costs lives. Scientific misinformation, especially coming from those in positions of power and trust, poses a direct threat to our global civilization. Now more than ever, our future as a species hinges on our collective ability to make fully informed and evidence-based choices when it comes to scientific decision making.

Is learning the science curriculum not enough?

In light of the examples discussed in the previous section, we suggest that scientific and digital literacy are skills as essential to current and future generations as counting, reading or writing were to citizens of the past centuries. However, according to a report from the National Literacy Trust, over half of the teachers at both primary and secondary levels 'believe that the national curriculum does not equip children with the literacy skills they need to identify fake news'. It is important to emphasize that the knowledge of the scientific terminology and facts (e.g., what is the function of mitochondria or the formula of Newton's second law) is only a partial (albeit essential) component of scientific literacy. To be able to think and work scientifically, students must possess knowledge not only of scientific facts, but also of the key elements of the scientific method (Figure 1) and wider context in which science operates, including the social and ethical implications of scientific progress. Individuals who are able to recall scientific facts but lack a holistic understanding of the underpinning scientific process are at risk of falling victim of scientific misinformation: while their recognition of some words and concepts may lead them to overestimate their understanding of the subject, they may not necessarily possess the skillset to critically

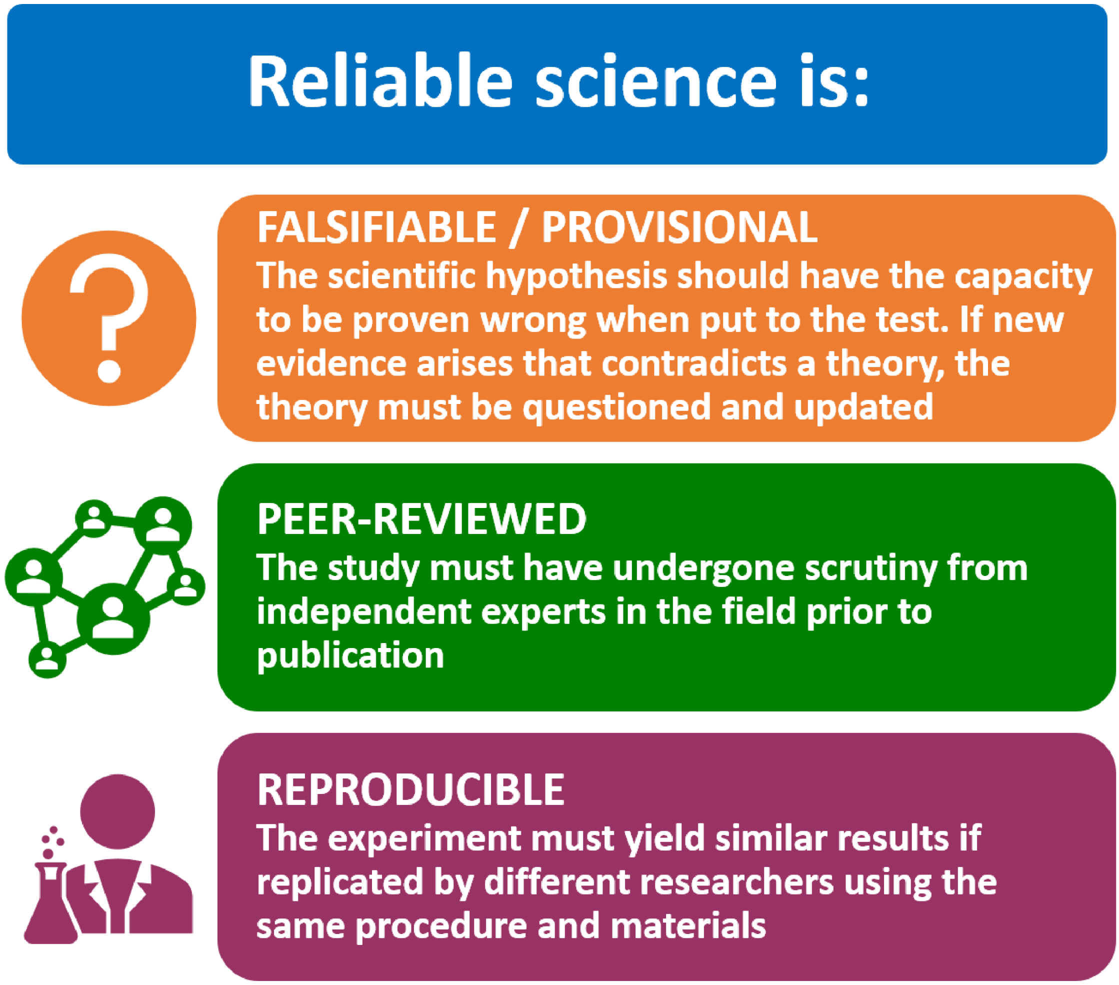

Figure 1. Key features of reliable science. It is worth emphasizing that this diagram is by no means an exhaustive list and that some elements (particularly the falsifiability aspect) may not necessarily apply to all fields of investigation.

evaluate the reliability of a source and the veracity of the information they are presented with (Figure 2).

Science is a core subject in most countries' educational systems at both primary and secondary levels. While most science curricula involve the teaching of key scientific notions and the rudiments of the scientific method, there is considerable inconsistency as to how (or indeed whether) students learn how to think and operate scientifically. Practical classes are an excellent way to reinforce theoretical concepts, engage students with science and foster their analytical and critical evaluation skills. However, for many students these skills often remain confined to the classroom context and do not translate to their wider mindset and future decision-making process. Using the example of the British educational system, scientific facts and notions (e.g., 'investigate the way in which water is transported within plants' and 'notice that light is reflected from surfaces') constitute the core of the primary science curriculum and are listed as 'statutory requirements'. The primary curriculum clearly identifies concepts like 'looking for different causal relationships in their data and identifying evidence that refutes or supports their ideas' or 'researching using secondary sources' as a part of 'working scientifically' and makes recommendations on how these elements should be embedded in the schemes of work within theoretical and practical classes. However, it is noteworthy that these aspects are frequently relegated to the 'Notes and guidance (non-statutory)' sections of the curricula, and may therefore be interpreted, implemented or assessed to a varying extent by different schools and teachers.

The secondary science curriculum consolidates the concepts and skills taught in primary school, including the 'working scientifically' aspects, which are to be embedded in the teaching of physics, chemistry and biology. The Key Stage 3 curriculum (years 7–9) introduces crucial concepts like 'objectivity and concern for accuracy, precision, repeatability and reproducibility' and 'understand that scientific methods and theories

Credible scientific sources

- Always contain a link or reference to the original peer-reviewed study
- Clearly point out the authors of the study and their academic affiliations
- Refer to up-to-date studies published on reputable academic journals
- Avoid absolute/overstated claims and tend to use a cautious language instead
- Make claims that reflect the empirical findings of the study being discussed
- Highlight the limitations of the study
- Are written professionally and very rarely contain grammatical or spelling mistakes
- Appeal to the readers' curiosity and rationality rather than trying to elicit an emotional response

Unreliable sources

- Do not provide links to peer-reviewed scientific articles, and cite blogs or social media channels as the original source
- Do not indicate the authors of the study and their affiliation, or cite authors that are not associated with a reputable academic institution
- Cite studies that can't be found in reputable scientific databases (e.g., PubMed, WebOfScience, Scopus) or are outdated
- Interpret correlation (e.g., X happens before Y) as causality (e.g., X causes Y)
- Cite statements or graphs out of context, twisting their original meaning
- Use a sensationalistic language to cause an emotional response in readers (e.g. anger or indignation)

Figure 2. Typical features of credible and unreliable sources of scientific information. Please note that this figure should be interpreted as general guidance rather than a 'one size fits all' checklist, particularly in the case of unreliable/malicious sources which are intentionally designed to mimic the features of a reputable source in order to mislead the audience.

develop as earlier explanations are modified to take account of new evidence and ideas, together with the importance of publishing results and peer review'. In the Key Stage 4 curriculum (years 10 and 11, the last stage where studying science is mandatory), 'working scientifically' builds upon the concepts taught in Key Stage 3, recommending notions such as 'appreciating the power and limitations of science and considering ethical issues' and 'recognizing the importance of peer review of results and of communication of results to a range of audiences'. However, these recommendations are implemented to a different (and frequently limited) extent in the subject specifications issued by the different exam boards that schools can choose for their GCSE courses. Schools, teachers and students fall under mounting pressure to achieve the best possible results in the final exams. With exam scores being linked to reputation (for schools), career progression (for teachers) and access to further/higher education (for students), it is easy to understand how recommended (yet essential) concepts that are not directly assessed may be de-prioritized compared to notions that are likely to come up in the exams.

It is worth noting that, while schools remain at the core of children's education, a significant proportion of their learning and development takes place outside the classroom context. A recent Ofcom report (see 'Further reading') highlighted that while talking to family and watching TV remained common sources of news, social media sites have largely replaced traditional news outlets particularly among younger generations. According to the Ofcom report, among teens aged 12–15, Instagram (29%), TikTok (28%) and YouTube (28%) were considerably more popular news sources than traditional media such as Sky News (19%), Channel 4 (10%) or the BBC (8%). If young people are consuming information outside of the classroom in what essentially amounts to an open forum with little to no policing in terms of fact-checking and reliability, it is essential that they are equipped with the critical and analytical skills required to identify misinformation. In the next section, we will evaluate existing initiatives that seek to address this endeavour, and make suggestions on how science curricula and outreach activities could be further developed in this sense.

Enabling tomorrow's citizens to recognize and avoid scientific misinformation

So what steps can be taken to ensure that students leaving compulsory education are equipped with the tools to discriminate facts from fiction and capable of a truly informed decision-making process when it comes to scientific matters? Every single person has the power to fight scientific misinformation and contribute to positive societal change not only in the voting booths, but also in their social behaviour. Even small everyday actions like questioning the reliability of a piece of information before sharing it on social media or respectfully challenging misinformation spread by friends and relatives go a long way towards limiting the spread of fake news.

While individual behaviours play an important role in contrasting scientific misinformation, compulsory education remains the cornerstone of any medium- and long-term effort. The emphasis attributed to 'working scientifically' in the national science curricula is certainly a step in the right direction, demonstrating the will to improve scientific literacy in future generations. To ensure that these recommendations come to fruition, it would be beneficial for curricula and exam board specifications to require that 'working scientifically' is not only considered a statutory element in theory, but that it is also fully and consistently embedded in schemes of work and linked to summative assessments at all levels.

Considering the often unsustainable workload and pressure they are already subject to, it would be unrealistic and unreasonable to place this burden wholly on class teachers. Primary teachers are expected to teach all subjects and therefore do not necessarily come from a science academic background. Secondary science teachers are required to possess a science degree; however, only some of them have worked in a research environment after graduating. Therefore, it is essential that teachers at all levels are supported and trained in the delivery of specialistic aspects of the science curricula such as what makes science reliable (Figure 1) and how to identify a credible source of information (Figure 2). Charities and foundations such as (among others) the Biochemical Society, Sense about Science, and the British Science Association promote initiatives to foster scientific literacy in adults and children. For example, participation in the CREST Awards had a measurable impact on students' science grades and their propensity towards pursuing further STEM studies.

These endeavours could be further facilitated by tapping into the expertise of research-active staff and postgraduate students in higher education institutions. Programmes like STEMunity, Scientists in School, or I'm a Scientist are all excellent examples of how initiatives led in synergy with higher education institutions can support schools in the delivery of specialized aspects of the science curriculum and foster scientific literacy skills in students.

Outreach programmes specifically dedicated to supporting teachers in the delivery of the science literacy aspects discussed in this article would benefit schools, universities and society at large. This paradigm would allow schools to reinforce their science teaching provisions without increasing teachers' workload, and universities to increase their visibility within local communities and foster students' engagement with science, potentially leading to improved recruitment and retention in their undergraduate courses. More importantly, a closer cooperation between schools and universities could be the key to enabling tomorrow's citizens to be critical thinkers equipped with the analytical skills that will allow them to rise up to the ever-increasing challenges that their future holds. ■

Further reading

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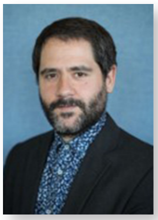

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