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Designing learning environments to promote competent lay engagement with science

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Abstract

An important goal of science education is promoting scientific literacy—the competence to interact with science as laypeople to solve problems and make decisions in their personal and community lives. This is made more challenging in an age of increasing science denialism. In this article, we discuss how to design learning environments for science education that can help students attain scientific literacy. We argue that science curricula should encompass lessons with two distinguishable foci. One focus engages students in understanding the reliability of science. The second focus engages students as laypeople interacting with science in the public sphere. We discuss these two curricular foci, presenting examples from our own work on designing and implementing instruction with the first focus.

1 | INTRODUCTION

A core goal of science education is to enable students to become scientifically literate and *competent outsiders* (Feinstein, 2011; Osborne, 2023). Competent outsiders are laypeople who are not scientists themselves but interact with science proficiently to solve problems and make decisions on issues that matter to them in their lives. For example, laypeople may need to make decisions about effective treatments for a disease that has struck a loved one, about actions to mitigate climate change, or about how to address the needs of a child with autism (Feinstein, 2014; Feinstein & Waddington, 2020). In this article, we discuss the design of learning environments that can promote the development of scientifically literate competent outsiders (cf. Höttecke & Allchin, 2020; Osborne & Pimentel, 2023). This article thereby contributes to the specification of what laypeople need to know to be competent outsiders.

A challenge to promoting competent outsiders who use science effectively in their lives is science denialism (Darner, 2019; Oreskes, 2019). In recent decades, a growing number of people express distrust of science and reject broadly accepted scientific claims (Oreskes, 2019; Osborne, 2023; Osborne & Pimentel, 2023). In this article, we address how educators can foster the development of scientifically literate competent outsiders in the context of increasing science denialism. We propose that fostering scientific literacy to solve problems and make decisions requires science educators to develop two distinct types of learning environments with distinct learning goals. We illustrate elements of our proposed solutions with examples from the *Developing Teachers' Epistemic Cognition and Teaching* (DeTECT) project, an advanced level science biology inquiry project focusing on biological systems.

2 | CHALLENGES IN DESIGNING SCIENCE INSTRUCTION TO PROMOTE SCIENTIFIC LITERACY

How can science educators design instruction to educate adults who are literate in science and can interact productively with science to address issues that matter to them? The most common approach in science education has been to assume that "*knowing science and 'thinking like a scientist' will help people solve their personal and policy problems*" (Feinstein & Waddington, 2020, p. 157). In other words, in science class students can learn practices of scientific reasoning that they can then apply as competent outsiders outside of school.

Is this approach likely to work? To answer this question, let us consider an instance of exemplary science instruction to promote scientific reasoning and ask whether students are likely to be able to apply this reasoning outside of school. Schneider et al. (2020) describe a unit that engages high-school students to think about the driving question: *Why do some objects take different amounts of time to fall from the same height?* (Schneider et al., 2020). Students observe and conduct experiments such as dropping two coffee filters stuck together versus a single coffee filter from the same height to see which hits the ground first. They use computer-based laboratory tools to investigate falling objects. Groups of students develop models to explain the phenomena they are observing and compare their models with other students' models, eventually developing a consensus model. Through these experiences, students engage in careful coordination of scientific explanations with evidence. Might this skill (coordination of explanations with evidence) transfer effectively to reasoning on topics outside of school such as the COVID-19 pandemic? We believe that the answer is no, and we discuss six reasons below. These six reasons point to how science education might be redesigned to do better at fostering reasoning outside of school.

2.1 | Commonalities are too abstract

Reasoning about falling objects and about COVID-19 can both be described as "*coordinating explanations with evidence*" at an abstract, or birds-eye, level. Although the reasoning in both topics does seek to coordinate explanations with evidence, the specific reasoning processes needed to unpack the use of evidence and explanations are very different across the two topics. In the physics class, students conduct straightforward experiments with clear-cut and mutually consistent results. In the case of COVID-19, most of the relevant data is observational and fraught with interpretive difficulties due to unavoidable confounds in naturalistic research, and people have to read and understand complex scientific reports or summaries of them rather than interpret simple observational experiments in class. Transfer becomes more difficult between settings that share fewer specific features (Day & Goldstone, 2012). To promote good reasoning outside of school, school environments should directly engage students with reasoning about the same sources of information that students will encounter in their lives, such as online documents, videos, and social media.

2.2 | School contexts are too epistemically "friendly"

There is another important difference between reasoning in school and reasoning out of school that makes transfer difficult. The information environment outside of school is much more epistemically chaotic, or *unfriendly*, than the school environment is (Chinn et al., 2021; Goldberg, 2013). An *epistemically unfriendly* environment is one with untrustworthy, confusing, conflicting information that makes it very difficult for people to determine what is true or accurate. Much of the evidence and information is of low quality, and many sources are not credible. This is characteristic of the contemporary digital world (Chinn et al., 2021). In contrast, science classes typically provide epistemically simpler, carefully curated, and in this sense *friendly* environments (Goldberg, 2013). For example, in the physics example described above, the challenges that students face when developing models are not too hard to overcome, and the evidence converges on a normatively acceptable conclusion. To learn to deal with the epistemic messiness, or *unfriendliness*, encountered outside school, students need opportunities to grapple with similar kinds of epistemic unfriendliness in school.

2.3 | Laypeople lack the expertise to appraise scientific evidence on their own

In science classes, students learn to coordinate models with evidence themselves, on topics that are simplified to a degree, so that they are not too technically advanced. But is it possible for laypeople outside of school to coordinate explanations with evidence themselves, on authentic science topics such as climate change? The answer is no because laypeople lack the expertise to do so (Chinn & Duncan, 2018; Höttecke & Allchin, 2020; Osborne, 2023; Osborne & Pimentel, 2023) along at least three dimensions of appraising evidence: evaluation, interpretation, and integration (see Duncan et al., 2018).

To appraise a body of evidence, laypeople need to be able to *evaluate* the methodological quality of each relevant study to determine how much weight each should be given. But laypeople lack the needed disciplinary knowledge to do so—such as advanced knowledge of statistical methods as well as knowledge of the highly specialised, technical procedures for conducting reliable research on any given topic. *Interpreting* scientific results similarly requires deep disciplinary knowledge of theory and findings from other studies. For example, when scientists interpret a study of the effect of a carcinogen on liver cancer in rats, they do so against a backdrop of knowledge of how similar the rat and human livers are, what other studies show about the extrapolation of findings from rats to humans across different systems, and so on. Laypeople cannot be expected to have this knowledge. Finally, laypeople lack the comprehensive knowledge needed to integrate the full range of evidence relevant to a topic. For many topics of interest, there are hundreds or thousands of relevant studies. To avoid basing judgements on cherry-picked evidence, one needs to have command over a full range of relevant studies. Only specialists who are well versed in the ongoing research on a topic are in a position to determine and appraise all of the relevant evidence. In short, human knowledge is bounded (Bromme & Goldman, 2014). People cannot be experts in more than one or a very few areas, and outside their own areas of expertise, they cannot coordinate models with evidence as experts do (Osborne & Pimentel, 2023).

2.4 | Too little emphasis on learning who to trust

The boundedness of human cognition means that when people cannot appraise evidence and claims oneself, they must trust others with more expertise (Bromme & Goldman, 2014). This means that much of science education, and education more generally, should prepare students better to learn who to trust. People need to work out who qualifies as relevant experts—those who thoroughly know the evidence on a topic and/or who have highly relevant experiences. They need to determine if there is an expert scientific consensus, and if so, which ideas are in consensus, and try to gain a sufficient understanding of these ideas. Thus, a key goal of science education should be to delve deeply into who to trust (Höttecke & Allchin, 2020; Osborne & Pimentel, 2023). However, most inquiry lessons in science education—such as the physics lesson described above—do not even refer to sources of information or to how consensus is formed among scientists, let alone prepare students to think about these matters (Chinn et al., in press).

2.5 | Understanding why science is reliable

To this point, we have argued that a strong focus of science education curricula should be activities that engage students as laypeople with bounded knowledge—engaging as competent outsiders who recognise that they do not have the expertise of scientists and must instead work out who to trust. Also, they need to learn about how consensus among experts is formed, which ideas are widely agreed upon, and so on. But how can students decide whom to trust? Should they trust scientists and the findings of science? In a world in which distrust in science is growing, there is a need for students to learn about why scientific research and practices are trustworthy, while acknowledging that science is uncertain and imperfect.

Science, when conducted properly, is trustworthy (Oreskes, 2019). But why? Students can readily see from social media and other digital sources that scientists regularly disagree with each other. Scientific advice on issues changes regularly—not only on more recent issues such as COVID-19 but also on issues such as the best diets to follow to reduce weight and sustain health. It is easy to find scientists who advocate partisan positions. On the surface, these do not seem to be features of a reliable way of knowing. So why should science be trusted?

To address these concerns, a core purpose of school science should be to examine and understand the practices that render science trustworthy. That is, science education should enable students to grasp why and how science can be reliable, despite superficial impressions of unreliability. Most current science instruction, like the exemplary physics unit described earlier, engages students in inquiry practices without sufficient reflection on the *reliability* of these practices. When students engage in scientific inquiry, they should reflect on why these activities make science reliable, and they should examine how the scientists use parallel practices that render real science trustworthy in similar ways.

2.6 | Accurate scientific knowledge is insufficient for addressing real world issues

Even if laypeople (or scientists) can attain accurate scientific knowledge, this knowledge is insufficient for real-world decision making and problem solving (Feinstein & Waddington, 2020). For instance, knowing the negative effects of air travel on the environment does not suffice to tell people whether they should fly. Other considerations must be weighed, such as the relative value of attending a conference and talking with colleagues in person or the need to visit an ailing family member. As another example, if a community needs to address eutrophication in a local pond, in addition to knowing the science of eutrophication, they need to consider how different solutions might play out given the details of this particular pond and the local political environment. Thus, to learn to use science as laypeople, people must not only work out what science says on an issue (such as by consulting scientists) but also how to use this knowledge alongside other sources of information to make judgements and inform actions (Feinstein & Waddington, 2020).

3 | TWO FOCI OF SCIENCE EDUCATION

Drawing on the analyses above, we conclude that science curricula need to encompass lessons with two distinguishable foci (cf. Osborne & Pimentel, 2023). One focus engages students in understanding the practices of science, with a focus on how and why science is reliable, despite the surface appearance of unreliability. This is the focus of *understanding the reliability of science*.

The second focus engages students with science *as* laypeople—not simulating the inquiry activities of scientists but engaging with science as laypeople do in their daily lives, reaching conclusions by reading information on the Internet, interacting with experts (e.g., their doctors), and so on. This is the focus of *engaging with science as laypeople*. In these lessons, students learn, among other topics, who to trust and how to identify issues on which there is consensus. They grasp that a warrant for trusting science is that scientists as a community use practices that contribute reliably to scientific knowledge. And they learn how to combine scientific information with other considerations to address personal, social, and civic issues.

In the second half of this article, we discuss these two types of curricula. We start by discussing a curriculum we are developing that addresses the first focus—understanding the reliability of science. Then we present some ideas for curricula that address the second focus.

Our analysis of the educational goals of the two types of curricula is grounded in the AIR model of epistemic thinking (Barzilai & Chinn, 2018; Chinn et al., 2014), which specifies three components of epistemic thinking (i.e., thinking directed at goals of developing representations of the world, such as models and theories). The first component consists of the *A*ims that people set and the value assigned to these aims—aims such as knowledge, understanding, or models. The second component specifies the epistemic *I*deals, or criteria, that people use to evaluate whether epistemic aims have been achieved, such as using the criterion of *fit with all the relevant evidence*, e.g., when evaluating claims about COVID-19. The third component—*R*eliable processes for achieving epistemic aims—includes the processes people can use to achieve their aims with a good likelihood of success. These processes include individual strategies (e.g., searching out multiple perspectives on an issue), formal methodologies (e.g., statistical procedures), and community processes (e.g., peer review of research by other scientists). In our analysis in the next two sections, we specify some of the *aims*, *ideals*, and *reliable processes* that should be addressed within each of the two curricula foci.

4 | UNDERSTANDING THE RELIABILITY OF SCIENCE

The first curricular focus area is *understanding the reliability of science*. Science lessons focused on understanding the reliability of science strive to enable students to understand how and why science is reliable despite its quite evident messiness. By the *messiness* of science we refer to the features and processes of science that make it appear on the surface that science is chaotic, fraught with controversy and disagreement, and therefore unreliable. In the following we list thematically features that have been identified to contribute to this "messiness" (Abd-El-Khalick & Lederman, 2023; Kienhues et al., 2020; Sinatra & Hofer, 2021).

Science is social. The social nature of science is in fact a key reason for its reliability, as we discuss later (e.g., Longino, 1990; Oreskes, 2019; Osborne & Pimentel, 2023). But the social nature of science may also make it appear *unreliable* to citizens: "*The fact that scientific truth emerges from a process of negotiations and agreements within groups of specialists may conflict with the everyday idea of scientific truth emerging through immediate experience, e.g., observations*" (Kienhues et al., 2020, p. 148). The prevalence of vigorous disagreements among scientists may seem to laypeople to be akin to the disagreements among politicians.

Science is influenced by values and cultural ideas. It is evident in the public sphere that many climate scientists not only investigate and report findings on climate change but also join in political movements to agitate for policies that will mitigate climate change. Citizens may view these activities as inappropriate for scientists (Kienhues et al., 2020).

Scientists engage emotionally with their work. A quick survey of Twitter shows that scientists' public criticisms of each other can be emotionally charged and accusatory. In reality, emotions such as curiosity, impassioned interest, and caring about improving the world are vital to the work of scientists (Thagard, 2008). But deep emotional engagement flies in the face of the public stereotype of the dispassionate scientist.

Science can be affected by bias. Like citizens, scientists are prone to cognitive biases such as confirmation bias (Solomon, 2001). Further, racist and sexist ideologies have influenced claims that scientists have made (Longino, 1990; Oreskes, 2019). These are clear threats to the trustworthiness of science, unless they are countered by practices that can render them less of a threat.

Uncertainty in science. Science is uncertain, in part because the natural world is recalcitrant. It is not easy to wrest successful scientific models and explanations from empirical investigations; the world resists easy explanation (Latour, 1999). Science in the making is highly uncertain, with many different explanations advanced and tested, until over a period of time (sometimes over decades) consensus is gradually developed. To laypeople watching science as it unfolds in real time, science may appear to be as chaotic and opinion laden as politics.

Instruction directed at improving students' understanding of the nature of science has emphasised that students should indeed learn about the *messy* features of science listed above. That is, they should learn that science is socially negotiated, emotion-laden, culturally and politically influenced, uncertain and tentative (Abd-El-Khalick & Lederman, 2023). They also emphasise *that* science is nonetheless reliable. But there is a need to go further—to enable students to understand *how* and *why* science is reliable despite the messy features that seem to undermine its reliability (Chinn et al., 2021). Why should not science be treated as just another form of politics when it is deeply influenced by many of the same factors (social controversy, values, ideology, cognitive biases, emotion) that also shape political positions?

Using the AIR model to guide our design, we have sought to begin to address such questions within our DeTECT project. This project builds on over a decade of research aimed at engaging students in computational modelling of complex biological systems (Yoon, 2022; Yoon et al., 2017). We have begun to identify aims, ideals, and reliable processes that scientists use to achieve reliable knowledge despite, and through, the messy characteristics of science. Our goal is to develop curricula that help students understand these so that the students will grasp why the products of these practices are trustworthy.

To this end, we have developed a new *nature of science* unit. Throughout the eight-lesson unit, students engage in a variety of activities to help them grasp how and why science is reliable despite its messiness. In several of these, students use agent-based simulations to determine which of several mitigations (including vaccination, masking, and social distancing) best protects human life during a fictional epidemic (based on swine flu). Students also evaluate reports of research investigating how the disease is spread.

To support understanding of scientific practices and their value, instructional interventions designed for the DeTECT project regularly encourage *meta-epistemic descriptions and justifications* (Chinn et al., 2020). *Meta-epistemic descriptions* are explicit articulations of epistemic aims, ideals, and reliable processes (e.g., stating that good models should fit all the evidence). *Meta-epistemic justifications* are reasons for why epistemic aims or ideals are valuable and for why epistemic processes are reliable. For example, a meta-epistemic justification for the ideal that an explanatory model should *fit all the evidence* could be that models that fit the evidence are more likely to be accurate. A meta-epistemic justification for the reliability of the methodological process of using large samples could be that large samples minimise the chance that one's findings are due to random outliers. The lessons that we designed for the DeTECT project encourage teachers to *prompt students* to provide meta-epistemic *justifications* for why aims, ideals, and processes are valuable, and to *provide* these justifications themselves. Meta-epistemic justifications of particular aims, ideals, and reliable processes can help students develop a rationale for why these are important.

Next, we briefly discuss how the unit endeavours to promote a grasp of the aims, ideals, and reliable processes that contribute to the trustworthiness of science.

4.1 | Aims

Scientists adopt many different overlapping aims—including developing models, explanations, laws, and theories. These aims have various kinds of value, including supporting understanding, accurate predictions, and practical decision making. The lessons that we designed for the DeTECT project encourage articulation of these aims and justifications for why they are valuable. For instance, as students develop models of how the epidemic can be mitigated, teachers can ask students why it is important to develop these models. Then they can point out that scientists, too, care about finding out which mitigations work the best so that lives can be saved.

4.2 | Ideals

The core epistemic ideal in science is empirical adequacy: models, explanations, and other epistemic products should fit the empirical evidence (Longino, 1990; Strevens, 2020). Unpacking this further, one can demand that the empirical evidence be of high quality (i.e., the evidence should be produced using strong methodologies) and that models and explanations fit as much high-quality evidence as possible (Kuhn, 1977). Scientists seek to meet other ideals, as well. For instance, some advocate the ideals of parsimony (better models are as simple as possible while still fitting the empirical evidence) and fit with other well-established theories (Kuhn, 1977). In science, these ideals are shared by the community, so that they use shared ideals to evaluate and critique their own and others' work (Longino, 1990).

To promote an appreciation of the value of shared ideals for good models, our DeTECT unit engages students in the public establishment of ideals for good models (adapted from Rinehart et al., 2014). The activity begins as groups of students construct a model that explains the unseen mechanism that propels a toy car. After creating their models and observing the models of other students, each group makes a list of characteristics of good models. Then the teacher leads a class discussion in which students develop an overall class list of ideals (or criteria) for good models. The list made by students in one class is illustrated in Figure 1.

As students develop these lists, teachers prompt the students to provide meta-epistemic justifications for their proposed criteria, and they may provide meta-epistemic justifications themselves. For example, one teacher justified why it is important to include *all* the evidence as follows:

> Do you want the vaccine developers to include all the data? Yeah. Yes. You don't wanna get the vaccine and then come to find out that they just ignored this one trial where half the participants died, right? […] That would be a little devastating if you got the vaccine and you found out that they just totally ignored this one outlier trial.
>
> (Cindy, teacher for period A for day 2 of Epidemic Unit, 2022)

This vivid justification helps students grasp why it is unacceptable to ignore some of the evidence.

Use of arrows to show relationships
Diagrams with labels and captions
Explanations
Key
Data
Fits as much good evidence as possible (reliable sources, use good science practices, multiple trials and data points)
Flexibility for alternate outcomes

FIGURE 1 One class's list of criteria for good models. *Note*: Each class developed a list analogous to this one following the procedure described in Section 4.2. *Source*: Authors.

Once students create these public criteria lists, they use them regularly to critique their own and their peers' models during modelling activities in class, as we discuss in the next section. In addition, teachers hold sessions in which students revise their lists of ideals for good models as the students gain additional experience with modelling. For example, students might alter an initial ideal that a good model "fits with evidence" to an updated ideal that a good model "fits with all the evidence." In this way, students can come to appreciate not only the value of epistemic ideals for developing knowledge, but also to see how it is possible for a community's ideals to be improved.

As students develop, refine, and use these ideals to guide their inquiry throughout the year, it is essential that teachers support students' reflection on what they are doing, so that they grasp the connection between their community ideals and their knowledge production. Teachers can also help students see that scientists engage in the same activities; for instance, reviewers of papers are often asked to evaluate submissions against criteria for publishing research.

Commitment to the ideal of empirical adequacy is essential to the reliability of science, but not sufficient by itself. The reliability of science equally depends on the use of a range of reliable processes for achieving empirical adequacy, which we discuss in the next section.

4.3 | Reliable processes

Scientific communities use many different reliable processes to create and refine models, explanations, and theories that meet their ideals (especially empirical adequacy or "fit with evidence"). Understanding the reliability of science requires understanding how these processes can help mitigate any negative effects of scientists' ideologies, biases, and cognitive fallibilities. We begin by discussing four reliable processes that we have introduced to students in our DeTECT unit, and then we briefly discuss several other processes that are among those that should be included in curricula focused on the reliability of science.

4.3.1 | Evidence-centred social critique using ideals for good models

A core process that contributes to the reliability of science is that scientists engage in *social critique* of each other's ideas, and they improve their ideas based on these critiques (Longino, 1990; Oreskes, 2019). Social critique includes not only peer review (reviewing, vetting, and improving articles prior to publication) but also the ongoing critique of ideas extending long after publication (Osborne & Pimentel, 2023). These critiques are performed in accord with scientists' shared ideals (Longino, 1990). For knowledge to advance, it is also vital that the community is open to diverse perspectives, that it takes critiques seriously, and is willing to change their ideas in response to them (Longino, 1990).

Social critique by itself does guarantee reliability. Vigorous social critique occurs regularly outside of science without advancing knowledge (e.g., parliamentary debates that generate intense heat but no consensual advance in knowledge). Social critique in science works to advance knowledge because it centres on iterative improvement of coordination of evidence and models. It is governed by shared ideals, including what Haack terms *a stiff regard for evidence* (Haack, 2007), which leads to a willingness to revise ideas.

The learning environments designed in the DeTECT project endeavour to help students grasp the value of evidence-centred social critique by engaging them in such critique, followed by reflection on how it is that the critique advances their ideas. As one example, in the activity in which students create models for analysing the functioning of a toy car, they subsequently share their models and evidence with another group. During this sharing, students discuss any questions that they have about each group's model, and they collaborate to figure out what further evidence could be gathered to answer those questions. Students then return to their own group, gather more evidence, and revise their models based on the discussions with their peers and new evidence. Whole-class reflections on these activities can help students appreciate multiple reasons for why social critique contributes to more reliable knowledge. For example, students can recognise that another group had insights into the limitations of their model that they did not think of, and vice versa. They learn of evidence that contradicts some part of their model, and they identify ways to gather new evidence to improve their models. Extending their reflections, teachers and students can observe how scientists use similar practices. These reflections can enable students to appreciate the reliability of evidence-centred processes of social critique.

4.3.2 | Developing and improving reliable empirical methods

Scientists develop agreed-upon methodological processes that are considered to yield reliable evidence—e.g., reliable methods for conducting experiments, for coding and analysing data, and for establishing the validity and reliability of measures. Ideas about good methods can be revised over time, and scientific communities should be open to diverse perspectives on methods in order to improve them. For example, it is now known that p-hacking (e.g., deciding on which statistical analytic method to use after one determines which one yields statistically significant results) undermines the reliability of statistical conclusions; as a result, scientific fields are now implementing methods such as preregistration of studies that guard against p-hacking (Gehlbach & Robinson, 2021).

Students and laypersons in general may be unaware that scientists develop and improve norms for good methods over time. Therefore, we introduce students to these reliable scientific processes in our nature-of-science unit. In one activity, students rank five pieces of evidence in order from the highest to lowest quality. The evidence varies in the quality of methodological elements (such as sample size, presence and quality of control groups, validity of measurements, etc.). Students then reflect together on how they have individually ranked their evidence, and based on their rankings, they generate a class list of characteristics of good scientific methods. They provide justifications for each item as they create the list to support an understanding of why these methods are reliable. Figure 2 shows an example of one class's list of characteristics of good scientific methods.

Students then use these characteristics of good methods productively throughout the year to evaluate their own and their peers' research. Like lists of ideals for good models, these lists of reliable methods can be revised over time, helping students to see the value of improving their methods. In parallel, students should learn about ways in which scientists engage in comparable practices to improve scientific knowledge production. Even when students and laypersons are aware that scientists improve theories and models over time, they may not be aware of the prevalence of processes for simultaneously improving empirical methods through critique.

4.3.3 | Critiquing each other's empirical methods

A means by which science improves knowledge is that scientists use their norms about good methods to critique each other's methods and—in response—conduct better studies. They often do so even before they conduct studies (e.g., grant advisory boards that critique proposed methods of upcoming studies). Our DeTECT unit engages students in these processes by having each group of students develop written plans for an empirical investigation, with justifications for each step. Then other groups move around the classroom and assess the written procedures of other groups, judging them by their class list of characteristics of good scientific methods and recording their critiques for the other groups to see. Students review the critiques left by their peers, revise their initial procedure, and perform the revised procedure. Through these steps, students can see that methods (and the resulting data) can be improved through community critique. Reflecting on how scientists use similar approaches can help them appreciate a key practice that contributes to the reliability of science.

Having measurable evidence (like a fever measurement) vs. just "I Feel Better" without having to worry of people's opinions
Being specific and having accurate details; such as how well something works or doesn't. (Don't say "most people", give a number or a specific measurement).
Having a non-variable in the experiment, a control.
Large sample size
Using accurate data with controlling different variables (age, general health) to make a conclusion.
Comparing and contrasting different ideas, communicating with others to find out which solution is best.
Including all evidence and running the experiment over a long period of time.

FIGURE 2 One class's list of characteristics of good methods. *Note*: Each class developed its own list analogous to this one, following the procedure described in Section 4.3.2. *Source*: Authors.

4.3.4 | Resolving disagreements

Scientists employ many strategies to resolve disagreements (Thomm et al., 2017). They may look for differences in the quality of methods to account for differing positions (e.g., disagreements about the effects of masking may arise because some studies use self-reported measures, whereas others make actual observations). They may look for differences in details of interventions or samples to resolve disagreements (e.g., discrepant results from experimental tests of a drug may arise because of differences such as the age of participants). They may attribute disagreements to scientists having different interpretative frameworks that cannot be resolved without further empirical investigation. To appreciate the reliability of science, it is helpful for students and citizens to learn about resolution strategies that scientists use to resolve disagreements productively.

In DeTECT, we have begun developing lessons to help students learn different ways to reliably resolve disagreements. For instance, during the nature-of-science unit, a prompt is used in one of the lessons to ask students to consider why different student groups got different results. For example, as illustrated in Figure 3, two groups reached different conclusions because one group ran just a single trial in the simulation, whereas the other group ran five trials. Students realise that, because the simulations are stochastic, multiple trials are needed to guard against results that are unduly influenced by outliers. By thus considering that better methods afford more trustworthy results, students learn one simple but reliable means of resolving disagreements. Over time, students should learn a broad range of reliable approaches for attempting to resolve disagreements. In this way, students can see that disagreements at the present time do not mean that science cannot be trusted, because scientists have a variety of means to resolve these differences over time.

4.3.5 | Other reliable processes that should be emphasised

As sketched above, we have begun designing DeTECT lessons to support students' understanding of processes that render science reliable despite its messiness. But this is only a start. It is beyond the scope of this article to

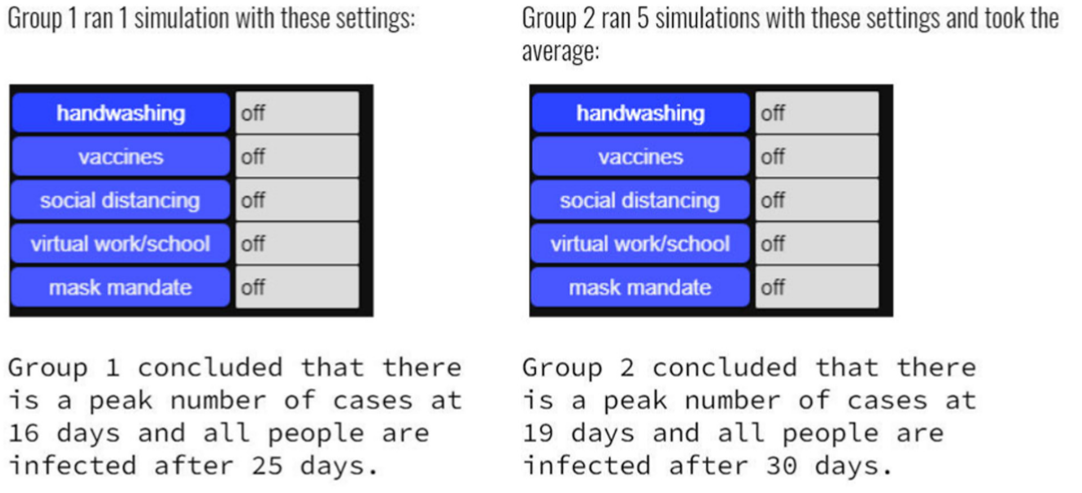

FIGURE 3 An activity in the epidemic unit that tasks students with resolving the disagreements between two studies. *Note*: Illustration of how students tried to explain the differences in results obtained by two groups of students on the basis of their simulation runs in the Epidemic Unit. A plausible explanation for different results is that one group ran the simulation once whereas the other group ran it five times. *Source*: Authors.

develop a comprehensive analysis of reliable processes that might be valuable to include, but we list several additional processes here that should be emphasised in science curricula:

- Much of science education exposes students to one or a few studies at a time, failing to communicate that science involves coordinating explanations with dozens or hundreds of studies. Thus, it is important for students to understand how *much* scientific evidence exists, and that scientists perform various types of syntheses (such as meta-analyses) to scrutinise and integrate a comprehensive range of relevant evidence.
- In many fields of science, such as evolution and climate change, empirical evidence is convincing because there are multiple lines of converging evidence from different areas of investigation. For instance, climate change models are supported by evidence from ocean surface temperatures, evidence of carbon dioxide levels in the atmosphere over time, studies of historical deposits of ice in ice cores from sites such as Greenland, studies of glacial changes, and many others. Students should learn about the empirical potency of such converging evidence, which is regularly sought, and often attained, through research (Samarapungavan et al., 2018).
- Scientists subject their own methods to empirical investigation, which provides further justification for the validity of these methods. For example, statisticians investigate statistical methods through Monte Carlo analyses and other studies. Studies on the effects of placebos established the need for double-blind studies.
- Even when scientists cannot yet agree on a best model, their empirical data can rule out many other explanations as unviable. It may be valuable for students to appreciate that science advances when alternatives are ruled out, and not only when there is consensus on a single model that is supported as the best one.

4.4 | Summary

In this section, we have identified some aims, ideals, and reliable processes that contribute to the reliability of science. It is an important goal for science education to help students appreciate how these contribute to the reliability of science, so that they can appreciate why science is trustworthy. They can then apply this understanding as they engage in lessons with the second focus—engaging with science as laypersons.

5 | ENGAGING WITH SCIENCE AS LAYPERSONS

The second focus area is about engaging with science as laypersons. This is the aim of the second type of lesson for promoting scientifically literate and competent outsiders. Lessons with this focus do not engage students in inquiry that simulates the practices of science (e.g., hands-on inquiry); instead, they engage students with science as laypeople. Students use information available to laypeople to address questions that matter to individuals and communities. Although we have not yet incorporated this type of lesson into the DeTECT project, we plan to do so in the future.

Curricula with this focus will engage students with science as laypeople do, through reading online sources of information, interacting with doctors and scientists, and so on (Feinstein, 2014). Lessons with this focus could involve documents-based inquiry, in which students use documentary sources such as those found on the Internet (including video and audio media) to answer question such as, "*Is bottled water safer to drink than tap water in our locale?*" Other lessons could include socio-scientific problems such as deciding what actions, if any, a coastal community should take to address rising sea levels due to climate change.

One goal of these lessons is for students to learn to identify who is trustworthy and to determine which issues have more or less expert consensus (Osborne & Pimentel, 2023). Scaffolds can be provided to encourage students to think about matters such as the trustworthiness of sources and how to identify and work with information about scientific consensus (e.g., Barzilai et al., 2020). Students can also reflect on how what they are learning about reliable practices of science (the first focus area) can inform their decisions about who to trust (the second focus area).

Another goal of these lessons is to learn to select relevant scientific information and combine it with other sources of knowledge (including personal experiences), in congruence with personal and community values, to address issues and problems. For example, scientific knowledge that coastal regions have a high probability of suffering frequent future floods due to climate change must be combined with economic knowledge and knowledge of local communities to determine what might be done in responses to this threat (Feinstein & Waddington, 2020).

The aims for lay engagement with science typically involve making decisions and solving problems in one's everyday life. The ideals for laypeople to use to determine the credibility of scientific claims include the trustworthiness of sources, the degree of acceptance of claims in the scientific community, validation or corroboration of claims by knowledgeable others (e.g., vetting of reports through peer review), and coherent integration of multiple sources of information (Duncan et al., 2018). Reliable processes that are valuable to laypeople include: identifying who experts are, including the level and relevance of their expertise, identifying sources of bias, evaluating how well published information has been vetted, determining whether there is consensus in the scientific community, identifying areas of agreement and disagreement among experts, considering different perspectives, and integrating information from diverse sources and perspectives (Duncan et al., 2018, p. 916; Feinstein & Waddington, 2020). Curricula directed at engaging students as laypeople in the public sphere should help students learn, apply, and reflect on these aims, ideals, and processes.

It is possible that an understanding of what makes science reliable might provide deeper insight into the types of experts and consensus that are most worthy of trust. For example, an appreciation that scientific claims should be grounded in all the evidence, and not just one or two studies, could lead laypeople to query whether evidence has been cherry-picked and to ask whether a reputed expert is actually familiar with all the voluminous evidence on a topic. Similarly, an appreciation that scientists constantly improve their ideas, evidence, and methods could spur scepticism toward experts who never mention evidence that might counter their position and who show no indication of being responsive to changing contours of evidence.

6 | CONCLUSION

To help students learn to reason well about scientific matters outside of school, science educators should create learning environments with two distinct foci. First, for students to have a proper warrant for trusting science, they need a deep understanding of what makes science reliable, despite its *messiness*. We have discussed some of the aims, ideals, and reliable processes that we think are vital to promote this understanding. We have also discussed how our DeTECT project for designing science learning environments has sought to engage students in inquiry activities that can help them understand these practices and why they are reliable. Curricula with this focus engage students in practices of scientific inquiry. This is done with the distinctive goal of enabling students to grasp the practices that contribute to making science a reliable source of knowledge. The goal is not merely to learn what the aims, ideals, and processes are but also to appreciate how and why they contribute to trustworthy knowledge. This may involve introducing practices (such as methods of disagreement resolution) that have not often been featured in science instruction to date.

The second focus is for students to engage as laypeople with science as they do in their lives out of school, and as they will do as adults. This means that students learn to make sense of information in the public sphere, using online documents, YouTube and TikTok videos, social media, interactions with experts, and other public means to reach conclusions and solve problems. The key questions become who to trust, who is a relevant expert, whether experts are in consensus, which ideas are most agreed upon, how to integrate scientific information with personal experience and other sources of information, and so on. This requires a curricular focus that engages students in engaging with science as laypersons, not as if they were junior scientists.

Research is needed to determine how best to design learning environments that achieve these goals. For example, what is the best order for introducing various reliable practices of science to students? How can students be supported in understanding why the practices they are engaged in are reliable, and to see that scientists are indeed using similar practices to create scientific knowledge? How should lessons with the two foci be interleaved with each other? Answers to these and other questions like them will help designers produce curricula that better prepare students to reason well as competent outsiders in the public sphere.

DATA AVAILABILITY STATEMENT

The data supporting the findings from this study are available from the corresponding author upon reasonable request. However, the data are not publicly available due to privacy restrictions.

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