Macrothink Institute™

Journal of Studies in Education
ISSN 2162-6952
2024, Vol. 14, No. 4

Teaching Students What Constitutes Scientific Evidence

Don A. Affognon

Department of Educational Psychology, University of Nevada, Las Vegas

4505 South Maryland Parkway, Las Vegas, Nevada 89154, USA

Telephone: (210) 773-7303 | E-mail: affognon@unlv.nevada.edu

Received: August 10, 2024 Accepted: Sep. 26, 2024 Published: November 1, 2024

doi:10.5296/jse.v14i4.22249 URL: https://doi.org/10.5296/jse.v14i4.22249

Abstract

What sets credible scientific claims apart from pervasive misperceptions and are there effective strategies for teaching college students to evaluate popular accounts of scientific evidence? The Next Generation Sciences Standards (NGSS) suggest that although the practices for developing credible scientific evidence vary across disciplines, there are common features. These include a commitment to using evidence as the basis for developing claims, gathering evidence to accept or reject student ideas about the causes of certain effects, and relying only on evidence to draw theoretical conclusions. Yet the NGSS do not clearly specify what counts as credible evidence. I defend the view that while there are no shortages of strategies for teaching evidence evaluation, the effective ones share two features: (i) they reflect how students generally interact with evidence, and (ii) they bridge the gaps between expert and nonexpert evidentiary practices.

Keywords: Science instruction; Evidentiary practices, Bayes' theorem, Instructional methods

1. Introduction

The question whether there are effective strategies for teaching college students how best to evaluate popular accounts of scientific evidence is not new. But it has become a great focus of academic inquiry, as more scholars wonder what to do about the proliferation of pseudoscientific information (Barzilai & Chinn, 2020). The question is of theoretical interest because it concerns two strikingly different phenomena: the manner in which students engage with evidence and the approach that professional scientists take. Whereas scientists use their disciplinary knowledge to judge the merits of scientific claims, students typically lack the knowledge and technical skill to comprehend what constitutes credible evidence (Feinstein, 2011; Keren, 2018). In an attempt to deal with this epistemic difference, the National Research Council led the implementation of the Next Generation Science Standards (NGSS) with the goal of creating a consistent framework for science education. But in the auxiliary documents backing the NGSS, only two stipulations deal squarely with evidence evaluation. Appendix F emphasizes that data are not evidence until used to support a claim, and Appendix H states that knowledge building with evidence is iterative, that scientific disciplines share common rules for gathering evidence, and that having different types of evidence produces better explanations (Next Generation Science Standards, 2013).

Yet neither appendix denotes what counts as credible or reliable evidence, much less what kinds of epistemic understandings or theoretical awareness students should have about the function of evidence in scientific knowledge-building. In other words, the NGSS offer insufficient guidance for teaching students evidentiary reasoning (Donnelly, 2006). The issue, according to Duncan et al. (2018), is that this limitation "creates a risk of perfunctory and simplified implementation of evidence-based practices that misses the intent of the standards or does little to prepare students for reasoning with the complex, varied, and contentious evidence encountered in popular media and in advanced education" (p. 907). In reaction to such a risk, Duncan et al. (2018) put forward a theoretical framework rooted in the observation that because current science instruction treats evidence in simplified ways, "students have few opportunities to realize that science progresses through diverse interactions with evidence—through accumulations of many kinds of evidence, through contentious processes of interpretation and reinterpretation…and through debates about methodologies…" (p. 909). Known as *Grasp of Evidence*, the framework elaborates the concept of evidence by casting it in five dimensions, the first four of which focus on what students ought to know about how scientists treat evidentiary information. The fifth dimension of the framework focuses on how students, and the larger public, draw conclusions from various evidence reports.

In line with the Grasp of Evidence (GoE) framework, I defend the view that although there are no shortages of strategies and methods for teaching evidence evaluation, the most reliable ones share two features: (1) They reflect how students generally interact with evidence, and (2) they bridge the gaps between expert and nonexpert evidentiary practices. In particular, I review the theoretical and conceptual frameworks underlying the instructional models that are considered effective for enabling collegians to accurately evaluate popular accounts of scientific evidence. The goal is not to present an exhausting list of such strategies but rather to draw attention to the academic theories and concepts that inspired them. Recognizing the extent to which instruction can either enhance or hinder students' ability to grasp what makes a piece of evidence scientific or unscientific, I conclude by presenting five instructional strategies and methods that appear to have produced measurable learning outcomes in the science classroom.

2. Literature Review

2.1 Background

Over the past 66 years, two reforms have shaped science education in the United States. The first was the 1958-1970 curriculum reform project sponsored by the newly formed National Science Foundation (NSF) in response to the Soviet Union's launch of the artificial satellite Sputnik in 1957 (Duschl, 2008). That event created such a persistent concern that the United States was falling behind in science and technology that in 1958 Congress passed the National Defense Education Act. The objective of the law was to create academic curricula that would enable students to think like scientists and be ready for major science careers (Rudolph, 2002). The second reform, which began in the 1980s, has now become an integral part of the US national science standards movement, whose clear intent is to "develop a scientifically literate populace that can participate in the economic and democratic agendas of our increasingly global market-focused science, technology, engineering, mathematics (STEM) societies" (Duschl, 2008, p. 1). One of the signature developments of this movement was the implementation of the Framework for K-12 Science Education, which recognized that preparing students to be competitive in the global STEM industry begins in K-12. The framework popularized the principle that attention must be paid to every aspect of the K-12 science curriculum (National Research Council, 2012).

An offshoot of the Framework for K-12 Science Education, the Next Generation Science Standards (NGSS) assert that even though the methods used across disciplines to teach scientific reasoning differ, they share certain features. Foremost amongst these is the reliance on data and evidence to make scientific claims (National Research Council, 2012). Moreover, the standards highlight the value of getting evidence from multiple sources. This detail is explicit in the NGSS description of practices (constructing evidence-based accounts of different natural phenomena), in the crosscutting concepts (generating evidence to support or refute ideas about the causes of specific effects), and in relation to the very nature of science (scientific knowledge originates in empirical evidence). Also, reliance on evidence is described as a major objective of the practice "engaging in argument from evidence" (NGSS Lead States, 2013, p. 26). But in all the auxiliary documents of the NGSS, only two stipulations deal with best practices in evidence analysis. In the practices of *planning and carrying out investigations* legible in Appendix F, there is a clear proclamation that "data aren't evidence until used in the process of supporting a claim" (NGSS, Appendix F, p. 7). And in the data-analysis and argument-from-evidence practices, a consistent emphasis is placed on the criticality of data analysis but also on the use of evidence to accept or reject claims. Building on its precursor, Appendix H affirms that "empirical evidence is the basis for scientific knowledge and that knowledge building is iterative and revisionary" (Duncan et al., 2018). Not least, Appendix H affirms that not only do all scientific disciplines adhere to the same set of rules for collecting, analyzing, and interpreting evidentiary information, they collectively share the belief that multiple sources of evidence yield better explanations and advance theory.

Yet neither appendix specifies what really counts as credible evidence, much less what kinds of epistemic understandings or theoretical awareness students ought to have about the function of evidence in scientific knowledge-building. For example, there is no mention of what features or characteristics of evidence should be of preponderant interest when separating the reliability or the validity of evidence from the credibility of its origins. Nor is there any mention of the kinds of epistemic understanding students should have about the importance of evidence in scientific knowledge-building, let alone how various types of evidence should be arranged in a cohesive unit from which to draw meaningful conclusions (Donnelly, 2006; Furtak et al., 2010). But the problem, as Duncan et al. (2018) have suggested, is that "without explication of the epistemic features and the roles of evidence and how students should engage with them, there is a risk of perfunctory implementation of evidence-based practices that misses the intent of the standards" (p. 909). For Chinn and Malhotra (2002), this problem is obvious in many classrooms where the use of evidence in science instruction is undeniably simplified, consisting more often than not of predictable experimental routines and analyses, or of foundational descriptions of scientific data. Likewise it is not unusual to see students relying on one or two pieces of evidence to draw causal or correlational inferences (Samarapungavan, 2018). But what makes the research problem we are talking about more disquieting is that relative to what they work with in the classroom, the kinds of evidence students encounter in popular media are more nuanced, more diverse in quality and strength, and often very controversial (Ruhrmann et al., 2015). All told, given the current use of evidence in science classrooms, it is unsurprising that students are defenseless when they face claims such as that the measles, mumps, and rubella (MMR) vaccine causes autism (given the # of parents claiming their children's autism appeared shortly after getting the MMR shot), or that the COVID-19 vaccine is ineffective and causes new variants of the virus to emerge and spread (given the # number of known reinfection cases). The question is, what can teachers do to equip their students with the tools they need to distinguish what is credible evidence from what is not?

2.2. Evidence in Research

A useful starting point for responding to the concerns expressed in the foregoing section is to elucidate what professional scientists mean when they ask, "Where is the evidence and how credible is it?" Taken in its broadest meaning, the concept of evidence has been an overarching focus of epistemology and the subject of analyses involving researchers of all stripes, including philosophers of science, biologists, theoretical physicists, and epistemologists themselves (Kelly, 2008). But to students and the public at large, what represents reliable evidence may not be clear. Consider the claims that: (1) given the number of documented cases of reinfections, the COVID-19 vaccine causes new variants of the virus to spread, (2) given the number of parents claiming that their children developed autism soon after receiving it, the MMR vaccine causes autism. In both cases, the type of evidence submitted is as explicit as the causal relationship it is meant to establish. Now consider how much difference it would make if instead of guessing whether to believe these claims, all collegians could make up their minds by using the law of probability that weighs the strength of evidence (Pinker, 2021). Bayes' theorem, as it is known, is reliable and practical for determining the credibility of all kinds of evidence; it stipulates how much to update or revise our probabilities (change our minds) whenever we encounter new evidence. The algebraic expression of Bayes' theorem is: $P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E|H) \cdot P(H) + P(E|\neg H \cdot P(\neg H)}$, where:

- P(H | E) is the posterior probability: the probability of hypothesis H given the evidence E.
- P(E | H) is the likelihood: the probability of evidence E given that the hypothesis H is true.
- P(H) is the prior probability: the initial probability of the hypothesis H before considering the evidence.
- P(¬H) is the prior probability that the hypothesis is false (it represents the probability of the complement of H).
- P(E | ¬H) is the likelihood of the evidence, given that the hypothesis H is false or untrue.

Using Bayes' theorem, we can now evaluate the first claim in these terms:

- H: The hypothesis that the COVID-19 vaccine causes new variants to spread.
- E: The evidence that there are documented cases of reinfections.
- P(H): The prior probability that the COVID-19 vaccine causes new variants is low, based on many reliable virology and epidemiology studies (Challenger et al., 2022).
- P(E|H): The probability of reinfections if the vaccine did cause new variants (possibly high if H were true).
- P(E|¬H): The probability of reinfections occurring naturally due to the virus's evolution is high because viruses naturally mutate and reinfections occur (Challenger et al., 2022).
- P(¬H): The probability that the vaccine does not cause new variants to spread is high (Challenger et al., 2022; see also Ruhrmann et al., 2015).

The takeaway is that the evidence supporting the claim that the COVID-19 vaccine causes new variants to spread is inconsistent or contradictory, given that: (a) reinfections occur naturally and the virus can mutate independent of the vaccine; (b) P(H) (or the prior probability that the COVID-19 vaccine causes new variants is low; and c) the probability of reinfections P(E | ¬H) or the probability of reinfections occurring naturally due to the virus's evolution) is high because viruses naturally mutate and reinfections occur without causing new variants to spread.

Likewise, we can evaluate the second claim in these terms:

- H: The hypothesis that the MMR vaccine causes autism.
- E: The evidence that a child developed autism after receiving the MMR vaccine.
- P(H): The prior probability that the MMR vaccine causes autism. Based on existing scientific studies, this is very low (Doja & Roberts, 2006; Gabis et al., 2022).
- P(E|H): The probability of developing autism given that the MMR vaccine causes it (high if H were true).
- P(E|¬H): The probability of developing autism, given that the MMR vaccine does not cause it, reflects the general autism rate in the population (Doja & Roberts, 2006).
- P(¬H): The probability that the MMR vaccine does not cause autism is very high based on all known or accessible scientific evidence (Doja & Roberts, 2006; Gabis et al., 2022; see also Pinker, 2021).

Here the takeaway is that this second claim is just as contradictory as the claim that the COVID-19 vaccine causes new variants of the virus to take hold, given that: (a) the prior probability P(H) is very low, b) P(E | ¬H) is high because autism typically develops around the age when children get the MMR vaccine, and c) the initial chances of the MMR vaccine causing autism is low and the chance of it not causing autism is high.

In a practical sense, Bayes' theorem is an algebraic expression of the idea that evidence analysis is an iterative process. The geocentric theory that the sun and the planets revolve around planet Earth is a paradigm case. Proposed centuries ago by the Egyptian mathematician and astronomer Ptolemy, the theory seemed rooted in solid observations and mathematical calculations. But that was before Copernicus, Galileo, and Kepler submitted new compelling evidence supporting the heliocentric theory which holds that along with other planets the Earth actually revolves around the sun (Adams & Slater, 2000; Shen & Confrey, 2010). More recently, the discovery of reverse transcriptase by the virologist and Nobel Prize laurate David Baltimore challenged the molecular biology central dogma or governing principle which held that genetic information only flowed in one direction: DNA to RNA to protein (Le Grice, 2012). Baltimore's findings (the new evidence) brought about a brand new pathway (RNA to DNA to protein) in the flow of genetic information and led the scientific community to revise its prior beliefs (Coffin & Fan, 2016).

Returning to the evidence given in support of the COVID-19 and MMR vaccine claims that did not withstand the rigor of Bayes' theorem, I used the word "contradictory" to emphasized that in both cases the evidence did not substantiate the claim for which it was advanced. But evidence evaluation is not a process that always leads to a binary (confirmatory or contradictory) outcome. According to Kelly (2018), the “weight” and “balance” of evidentiary information matter just as much. Whereas the weight of evidence relates to how substantial it is relative to a given claim, its balance relates to “how decisively it speaks for or against that claim. For example, the evidence supporting the claim that vaccines save lives is not merely confirmatory, it is also strong” (Doja & Roberts, 2006; Gabis et al., 2022). But if the credibility of a piece of evidence comes from a multiple of sources that are susceptible of Bayesian updating (Pinker, 2021), then what specific theoretical and conceptual frameworks align closely with some of most the effective strategies and methods for teaching students how best to evaluate popular accounts of scientific evidence?

2.3. Theoretical Frameworks

When it comes to linking strategies for teaching students evidence analysis to a larger body of knowledge, five theoretical frameworks: Vygotsky’s Sociocultural Theory, Walton’s Dialogue Theory, Duncan et al.'s Grasp of Evidence Framework, Hofer and Pintrich’s Epistemological Beliefs Framework, and Toulmin’s Argumentation Model. A seminal work, Vygotsky’s theory considers cognition to be a construct emerging from students’ interactions with the sociocultural environment in which they are (Kozulin, 1995). The usefulness of this theory lies in the Zone of Proximal Development (ZPD), which is to the space between what students can achieve on their own and what they can achieve with the help of a teacher. For Smagorinsky (2009), the ZPD is an effective bridge to higher cognitive grounds but also a template for the internal processing of sociocultural tools. Although the theory provides several pathways for using scaffolding, dialogic teaching, and a plethora of cultural tools for enhancing critical thinking, it carries a macroscopic view of how sociocultural interactions shape learning (Marginson, 1999).

But the relevance of Vygotsky’s Sociocultural Theory of Learning is not limited to social studies or language education. In a review titled “Learning Science in a First Grade Science Activity: A Vygotskian Perspective,” Shepardson (1999) used Vygotsky’s theory as a tool for investigating how education practices can constrain or facilitate children’s thinking and science knowledge building. Drawing from the results of a previous study involving twenty-four first graders who explored butterfly and beetle metamorphosis, the author clarified that in the children’s zone of proximal development, there were teachers guiding students’ observations and peers debating about each other’s ideas. Upon reviewing the data collected during, Shepardson (1999) argued that, in alignment with Vygotsky’s theory, the children's understanding of science concepts, such as *metamorphosis* and *biological life cycle stages*, was influenced by social interactions in the form of conversations with teachers and peers. The theme emerging from the aforementioned studies is that although Vygotsky’s Sociocultural Theory has been used in science education, it features prominently in language learning research studies where the sociocultural dimensions of his research are most pertinent.

An analog of Vygotsky’s Theory, Walton’s Dialogue Theory “recognizes that arguments unfold in the dialectical interchange between two or more parties" (Nussbaum, 2011, p. 87). The theory differs in one material respect: It assumes that an argument is warranted only if it is undefeated after the back and forth that often characterizes dialectical exchanges (Pollock, 1987, as cited in Nussbaum, 2011). This distinguishing feature is worth noting because in science education and especially in evidence analysis, it matters to show students why collaborative argumentation is also a process by which to let the strongest or most credible claims stand on their own merits (Hughes, 2021). It follows that Walton's theory can be useful in science instruction, perhaps to enhance collaborative reasoning or to study how students generally engage in problem-solving activities involving critical questions or requiring structured argumentation (Nussbaum, 2011; Nussbaum & Edwards, 2011; Pollock, 1987). But the theory bears relevance in fields ranging from law and artificial intelligence to cognitive psychology.

In the paper "Examination Dialogue: An Argumentation Framework for Critically Questioning an Expert Opinion," Walton (2006) discusses a specialized form of dialogue called examination dialogue, in which a person questions an expert for the sole purpose of evaluating the reliability of certain information. For to the author, this type of dialogue promotes critical thinking because it requires the questioner to probe the expert's assertions or test them against documented facts. As described, examination dialogue is in fundamentally relevant to science instruction, where students must develop the ability to critically assess the validity of various science reports and evaluate popular accounts of scientific evidence (Samarapungavan, 2018). Even so, the theory has a number of limitations that make using it to see how to teach students evidence analysis difficult. It relies heavily on context, and the effectiveness of dialogue types vary depending on the situation, making it difficult to generalize its application.

Even so, Rapanta and Christodoulou (2022) have looked closely at how Walton's theory can be used in science education. In "Walton's types of argumentation dialogues as classroom discourse sequences," the authors relied on the theory to place teacher-student interactions into four types of dialogues: *information-seeking*, *inquiry*, *discovery*, and *persuasion*. Upon studying interview transcripts from natural and social science lessons, Rapanta and Christodoulou (2022) reported that these four types of dialogue could be integrated so as to constitute a structured strategy for advancing critical thinking and profound engagements with science content. The findings of the Rapanta and Christodoulou study confirm that using Walton's theory facilitates the identification of novel dialogic pathways in classrooms and promotes students' reasoning skills, both of which are very useful whenever learning outcomes depend on critical thinking and deep understanding.

If Vygotsky's Sociocultural Theory of Learning and Walton's Dialogue Theory have a common denominator, it is that they place a strong emphasis on the multiple sociocultural underpinnings of learning and exemplify the collaborative aspect of argumentation (Kozulin, 1995; Marginson, 1999; Nussbaum, 2011; see also Rapanta & Christodoulou, 2022). But in the context of science instruction, these theoretical frameworks give little insight into what college students' cognitive processes for assessing popular accounts of scientific evidence are.

For sure, neither theoretical framework offers adequate insight into the question of how students' cognitive processes change when they engage in collaborative evidence evaluation tasks. Duncan et al.'s Grasp of Evidence Framework fills these major gaps. In Duncan et al.'s (2018) "Grasp of evidence: problematizing and expanding the next generation science standards' conceptualization of evidence," the authors assert that the main purpose of "this framework is to complexify the concept of evidence in ways that will facilitate introducing more authentic forms of evidence and more sophisticated ways of engaging with evidence in science classrooms"(p.907). The Grasp of Evidence (GoE framework) specifically "focuses on promoting the lay grasp needed by competent outsiders as they engage with science in their everyday lives" (p. 908). Even more specific, the framework articulates five dimensions, the first four of which represent what students should know about how experts work with evidence—evidence collection, analysis, interpretation, and integration. Unlike Vygotsky's theory and Walton's, the GoE framework is not primarily concerned with the larger sociocultural contexts in which students operate. Rather, it narrows its scope to the level of the classroom and proposes science-specific strategies and methods for teaching evidence evaluation. As such, the GoE framework is fundamentally concerned with advancing scientific literacy—or how students view or treat scientific evidence (Chinn & Malhotra, 2002; Duncan et al., 2018; Feinstein, 2011).

The overall picture implies that whereas Vygotsky's Sociocultural Theory is clearly foundational, developmental, and socially centered, Walton's Dialogue Theory is focused on dialogic learning, critical thinking, and productive argumentation. And as previously stated, these two frameworks have broad applications across academic fields. On the other hand, the GoE framework is narrow in scope but far more adequate for exploring the psychological mechanisms underlying the ways in which many students reason with and about the evidence they encounter in science classrooms and in popular media (Samarapungavan, 2018). So it is no surprise at all that the GoE framework has informed instructional strategies that emphasize the critical analysis of evidence, particularly in science. Among these are: (i) scaffolded instruction, where the framework supports the gradual development of evidence-based reasoning; (ii) active learning, where students engage in practical problem solving; and (iii) metacognitive training, where the GoE framework encourages students to use metacognitive prompts to reflect on how they assessed the quality of evidence in a number illustrative classroom experiments.

Turning to the last two of the five theoretical frameworks we have begun reviewing, I must say that while Hofer and Pintrich's Epistemological Beliefs Framework is an elaborative work, Toulmin's Argumentation Model is a foundational one. According to Barzilai and Chinn (2018, 2020), what makes the Epistemological Beliefs Framework useful in science instruction is that it rests on the idea that students hold different beliefs about the nature of knowledge and knowing and that those beliefs have a measurable impact on the way they process information and engage in activities that require critical thinking, such as evidence analysis. The framework proposes that beliefs about knowledge are distributed along four dimensions: (i) the ***certainty of knowledge*** (whether knowledge is fixed or fluid), ***simplicity***

of knowledge (whether knowledge is treated as an isolated set of facts or as interconnected concepts), ***source of knowledge*** (whether knowledge is externally granted or constructed internally), and ***justification for knowing***—the ways in which students and the larger public evaluate and justify knowledge claims (Hofer & Pintrich, 1997). Unsurprisingly, this framework encourages adopting strategies that challenge students' existing beliefs, promote reflective thinking and evidence evaluation, and bestow on students a real sense of appreciation for the complexity and uncertainty immanent to scientific inquiry (Barzilai & Chinn, 2018, 2020). But because the framework uses syllogistic logic, which builds on absolute premises, it is not ideal for capturing the probabilistic aspects of evidence analysis (Goel, 2007).

In an integrated review titled "The Development of Epistemological Theories: Beliefs About Knowledge and Knowing and Their Relation to Learning," Kneupper (1978) presents Toulmin's Argumentation Model as a potential alternative to Hofer and Pintrich's Framework. Toulmin's model, the author argues, focuses on the relationships between claim and evidence, along with the consideration of potential counterarguments. Specifically, the model integrates and promotes a comprehensive approach to argumentation that empowers students to critically evaluate the strength and validity of their claims in various contexts (Kneupper, 1978; see also Nussbaum & Edwards, 2011). Like Hofer and Pintrich's framework, Toulmin's model evolves across several dimensions, as it reduces arguments to these six overarching components: *claim*, *data, warrant*, *backing*, *qualifier*, and *reservation*.

Taken together, these dimensions allow for a nuanced and flexible approach to argumentation that makes the model useful in teaching students how to reason with and about evidence (Duschl, 2008). Better still, according to Furtak et al. (2010), integrating this model in science instruction enables students to sharpen their critical thinking skills and enhances their ability to effectively evaluate scientific evidence.

Though in its emphasis on claims, evidence, reasoning, consideration of alternative explanations, and integration, Toulmin's model is congruent with Duncan et al.'s GoE framework, the latter goes further and gives more credence to the three components of epistemic cognition: *epistemic goals*, *epistemic ideals*, and *epistemic processes* (Barzilai & Chinn, 2018). According to Duncan et al. (2018), epistemic goals are the epistemic outcomes that people set out to achieve, epistemic ideals are the criteria for ascertaining whether epistemic goals have been achieved, and epistemic processes are the means by which epistemic goals are achieved. As a result, Duncan et al.'s Grasp of Evidence Framework seems more practical than Hofer and Pintrich's Epistemological Beliefs Framework and Toulmin's Model, at least insofar as it specifies and leverages the ways in which claim and evidence interact in the realms of scientific reasoning (Samarapungavan, 2018).

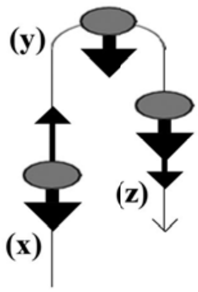
2.4. Conceptual Frameworks

Unlike theoretical frameworks, which make it easier to connect an instructional strategy to a wider body of knowledge, conceptual frameworks are adaptable and more specific (Hughes, 2019). They serve as maps, or as systems of ideas, with which serious academics can plan or carry out great research studies (Maxwell, 2013). Having probed the boundaries of Vygotsky's Sociocultural Theory along with those of Walton's Dialogue Theory, Duncan et al.'s Grasp of Evidence Framework, Hofer and Pintrich's Epistemological Beliefs Framework and Toulmin's Argumentation Model, let us examine four conceptual frameworks that have been reflected in strategies designed to enable students to distinguish scientific from pseudoscientific evidence.

2.4.1. *Epistemic Cognition and Conceptual Change*

Epistemic cognition is the process by which people construct, evaluate, and utilize knowledge (Barzilai & Chinn, 2018). Greene and Yu (2016) concur with this definition and go on to argue that students' epistemic cognition and beliefs predict "many academic outcomes…" (p. 45). In the paper titled "Educating Critical Thinkers: The Role of Epistemic Cognition," these authors described the role epistemic cognition plays as a psychological process that fosters the critical thinking skills students need to make sense of complex and controversial issues (Green & Yu, 2016). In their view, the 21st century presents so many unusual challenges involving science that teachers need to find ways to enable students to reflect on their own epistemic beliefs. And the reason is that students who hold evaluativist beliefs, which acknowledge the complexities and evolving nature of knowledge, tend to do better academically and are prone to integrating new information into their existing knowledge frameworks (Greene & Yu, 2016). The logical implication is that depending on their epistemic cognition and beliefs, students will find it easy or hard to understand the concepts underlying different models and to use them to tell what is scientific evidence apart from what is not (Barzilai & Chinn, 2018; Greene & Yu, 2016).

But can science instruction succeed when a student holds an absolutist view of science facts? According to educational psychologist Andrea diSessa, the answer is yes. In "A History of Conceptual Change Research: Threads and Fault Lines," diSessa (2014) provides a reasonable assurance that even absolutist epistemic views can change if instruction is consistent enough to upend epistemic beliefs. But as the author has emphasized, conceptual change is hard because it requires students to reassess their foundational understanding of the world in a way that clashes with their deep intuitive beliefs (diSessa, 2014). For example, let us consider these two figures:

Figure 1


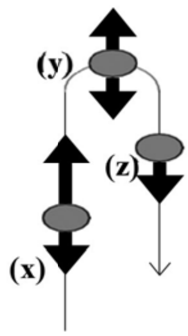


Figure 2

Note: Adapted from "A History of Conceptual Change Research: Threads and Fault Lines," by diSessa, A., 2014, *UC Berkley Previously Published Works,* p. 2-3.

Figure #1 depicts the way an expert, such as a physicist, conceptualizes the tossing of a ball into the air: (x) Gravity (thick arrow) directs the velocity of the ball's (thin arrow) downward, and (y) bringing it to zero at the peak, and (z) gravity extends its velocity downward in the fall. For any expert, only one force moves the ball all the way up into the air and pulls it back to the ground. But for a neophyte, the conceptualization of the same event is shown in Figure #2: (x) A force, generated by the tossing hand, drives the ball upward, (y) that force gradually decreases and comes to balance with gravity, and (z) the force is overcome by gravity, which drives the ball to the ground. For the novice, not one but two forces are involved in this event. This dichotomy is what conceptual change, or the ways in which teachers deal with misconceptions of this kind, is mostly about. But addressing misconceptions is only half of the challenge. The other half is that students who show up in the classroom with flawed ideas typically believe that theirs are the only reasonable ideas (Hewson, 1981). Under these circumstances, what should educators do?

One approach appears irresistible. It consists in arguing students out of their prior conceptions and persuading them to accept the scientifically accurate conceptualizations. But according to diSessa (2014), this approach assumes that students' prior knowledge forms a coherent whole, when in fact it consists of many quasi-independent elements. For this reason, diSessa (2014) emphasizes that instead of entirely rejecting student misconceptions, teachers should focus on turning the most productive of the flawed ideas that students express into normative concepts. Here is an example that builds on the ball toss experiment: "Students see balancing at the peak of the toss. But balancing is a rough version of conservation of energy, an incredibly important principle in physics. Similarly, the upward 'force' in the incorrect explanation is not absent, but it is precisely what physicists call momentum" (diSessa, 2014, p. 3). The point is that whenever feasible, teachers can and should use students' flawed ideas to introduce concepts that are most congruent with their epistemic beliefs.

2.4.2. *Motivated Reasoning and Inoculation Theory*

Two conceptual frameworks that deal with how students and the public react to information that challenges their existing beliefs, motivated reasoning and inoculation theory, are grounded in the assumption that people process information in a manner congruent with our pre-existing attitudes toward science, religion, politics and a number of subjects (Compton et al., 2021). According to Pennycook and Rand (2019), motivated reasoning is a cognitive bias which conditions people to accept information that supports their existing views while disregarding or being very critical of evidence that contradicts those views. In the context of science education, motivated reasoning plays a dual role. On one hand, it acts as a barrier to learning when students selectively accept information that aligns with their preconceived notions, which leads to a skewed understanding of scientific concepts (Druckman & McGrath, 2019). On the other hand, teachers can harness motivated reasoning to better engage students by connecting new scientific information to their preexisting ideas and by using teaching strategies that lead students to more critical evaluations of evidence (Pennycook & Rand, 2019). Although motivated reasoning and inoculation theory share the same core assumptions, the former is a descriptive framework that proposes a way to explain why people resist changing their questionable beliefs, while the second is a prescriptive one because it proposes strategies for literally "inoculating" students against the pseudoscientific evidence they see in popular media (Johnson and Madsen, 2024).

In the paper they titled "Inoculation Theory in the Post-Truth Era: Extant Findings and New Frontiers for Contested Science, Misinformation, and Conspiracy Theories," Compton et al. (2021) describe inoculation theory as a conceptual framework which effectively claims that people can be "inoculated" against unreliable information by way of recursive exposures to unscientific claims. For Compton et al. (2021), this process of inoculation process works the same way medicinal vaccines do: It builds cognitive resistance to falsehood by preemptively showing euphonious arguments that have no basis in truth. But as the authors note, inoculation theory "relies on two main mechanisms: forewarning of a counter-attitudinal attack to motivate resistance and a preemptive refutation of the attack to help model the counter-arguing process" (Compton et al., 2021, p. 3). The usefulness of inoculation theory is that it can be used to equip students with the technical skills they need to understand scientific reasoning, to distinguish scientific evidence from unscientific rhetoric, and to recognize or refute unsubstantiated claims arguments (Johnson & Madsen, 2024). But like any other framework, inoculation theory has its limitations. One is that presenting counterposing documented facts to a given misinformation may in some cases reinforce the misinformation. Another limitation is that the effectiveness of inoculation vary according the cognitive abilities, openness to new information, and levels of skepticism of the concerned parties. Finally, the initial "immunity" against misinformation can weaken so that periodic re-exposure may be required to maintain resistance (Ivanov et al., 2020).

As we have seen, conceptual frameworks offer a flexible structure for how educators understand and resolve many instructional challenges. They often embed multiple theories and can provide a customized, practical approach to designing instruction. Unlike theoretical frameworks that are more abstract, conceptual frameworks are problem-specific in that they draw on various theories to build models or strategies that cater to specific learning objectives (Anderson & Burns, 1990). As such, the conceptual frameworks we have looked at have served as roadmaps for addressing specific educational problems. Epistemic cognition and Conceptual Change Frameworks have indeed been used to develop instructional strategies intended to address students' resistance to changing deeply held misconceptions in science, such as misunderstandings about evolution or anthropogenic climate change. These frameworks help develop strategies that promote students' reflection on the nature of scientific knowledge and engage them in cognitive conflict to trigger conceptual change (Sinatra et al., 2014). Similarly, motivated reasoning and inoculation theory have been used to design or improve instruction intended to address the pervasive problem of students dismissing credible scientific evidence as a result of political bias. The bottom line is that while motivated reasoning makes it easier to understand why so many students cling to a plethora of misinformation, inoculation theory offers teachers a user-friendly tool for building resistance by repeatedly exposing students to all kinds of pseudoscientific information and by showing them how motivated reasoning insinuates itself in the human mind and can affect the way that otherwise reasonable people decide what is true or not, especially under conditions of uncertainty (Cook et al.,2017). But whether theoretical or conceptual, the frameworks we have reviewed serve one more purpose. We can use them to address a design or instructional strategy problem in cases where, for example, the initial goal is to trace a specific classroom problem to its constitutive sources.

3. Instructional Strategies

The theoretical and conceptual frameworks we have looked at have informed the design and implementation of several instructional strategies (Hattie & Yates, 2014; Mayer et al., 2009; Moreno & Mayer, 2007; Nussbaum, 2011; Vogel-Walcutt et al., 2011). But according to Barzilai and Chinn (2018) and Donnelly (2006), when it comes to teaching students how best to evaluate evidence, the strategies that have produced optimal outcomes have a common denominator: they integrate the cognitive and metacognitive aspects of learning, emphasize the evolving nature of science, and take students' epistemic beliefs into account. Put differently, effective strategies for teaching evidence analysis reflect: (1) how students typically reason with or about evidence and (2) they bridge the gap between expert and nonexpert evidentiary practices. One such strategy is active learning. According to Freeman et al. (2014), active learning has been shown to promote students' ability to objectively analyze evidence. Indeed in the meta-analysis they conducted to address the question of how to teach students best evidence evaluation practices, Freeman et al. (2014) found strong evidence that group debates and collaborative problem-solving measurably enhance student performance in science, engineering, and even mathematics. According to the authors, the reason is that these activities promote a deep understanding of scientific principles and enable students to apply their critical thinking abilities to real-world situations.

Another practical strategy is scaffolded instruction. It is known to play a significant role in the development of students' ability to evaluate evidence. In "Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work," Reiser (2004) explained that when students get structured support and are gradually introduced to increasingly complex tasks, they are better prepared to understand the complexities of scientific inquiry. As well, scaffolded instruction facilitates cognitive development and creates a context in which students build their confidence, which leads them to sophisticated understandings of procedural knowledge such as evidence analysis (Reiser, 2004; see also Reiser & Tabak, 2014). Metacognitive training is yet another device for enhancing students' evaluative skills. In one study, Zohar and David (2008) showed that explicit teaching of meta-strategic knowledge—encouraging students to reflect on their own thinking processes and recognize cognitive biases—measurably improves their ability to critically evaluate scientific evidence. Unlike scaffolded instruction, this approach empowers students to be more aware of their own patterns of reasoning and leads them to a more objective understanding of the relationships between evidence analysis and the scientific method.

The fourth strategy that has produced notable outcomes is interdisciplinary in that it seamlessly integrates media literacy with science instruction. In a study titled "The Importance of Teaching and Incorporating Media Literacy in Science Education," Fortner and Meyer (2000) illustrated the criticality of incorporating insights from media studies into science curricula and showed that this integration enables students to distinguish scientific information form the unscientific reports they encounter on many social media platforms. For Fortner and Meyer (2000), interdisciplinary teaching strategies equip students with the technical tools they need to navigate the increasingly complex information landscape in which they find themselves.

The fifth strategy worthy of attention hypothetically leverages the use of technology and digital devices and enables teachers engage students inside and outside the science classroom. To test the hypothesis, Clark et al. (2011) carried out a study to find how effective it is to use interactive video games to teach Newtonian mechanics. What they learned was that by using video games and other such technologies to immerse students in conceptually integrated learning experiences, teachers can enhance students' understanding of any number of scientific concepts. As a result, the authors argued that by designing interactive learning environments in which they can apply their knowledge and critically assess all kinds of evidence, teachers can help students sharpen their ability to tell scientific evidence apart from its opposite and be prepared to act as informed citizens in an ever-complex world of information.

4. Conclusion

At this point, it is tempting to conclude that by not specifying what constitutes credible scientific evidence, the Next Generation Science Standards have created a major "risk of perfunctory and simplified implementation of evidence-based practices that misses the intent of the standards or does little to prepare students for reasoning with the complex, varied, and contentious evidence encountered in popular media and in advanced education" (Duncan et al., 2018, p. 907). But the conclusion is unnecessary. Like many education standards and policies, the NGSS are designed to evolve and be updated over time. That means the responsibility of translating the NGSS into day-to-day school practice and tackling the under-specification problem that I have raised falls on the shoulders of those running the science classroom. And as we have seen, teachers can rely on a number of effective strategies to equip students with the technical knowledge they need to distinguish scientific evidence from unscientific evidence. Even though the literature review did not suggest that the five strategies I presented make up a complete list, it did suggest that active learning and engagement, scaffolded instruction, metacognitive training, technology-enhanced learning, and interdisciplinary approaches are effective for teaching students evidence analysis. What makes these strategies effective in science instruction is that (1) they account for the ways in which students interact with evidence, (2) they treat students' prior knowledge and epistemic beliefs as opportunities for bridging the gap between expert and nonexpert evidentiary practices.

What is also important is that the literature review revealed that while many studies have taken up the question of what strategies are effective for teaching students how best to assess popular accounts of scientific evidence, several research gaps remain. First, there is an obvious lack of longitudinal studies looking at the long-term impact of any effective strategies. Second, fewer studies have taken up the question of how to integrate epistemic cognition and critical thinking and scientific reasoning. Furthermore, because the effectiveness of a strategy may vary across educational contexts and student populations, additional research is needed on context-specific instructional models. It follows that not only does this paper throw a spotlight on the strategies teachers can use to teach best evidence analysis practices, it proposes practical ways of arming students against various unscientific claims. It can also serve as a springboard for exploring the epistemic goals students set for themselves whenever they must reason with or about evidence. Probing these goals and examining how they might be reshaped by certain interventions could advance pedagogical practices and make way for targeted inquiries into the strategies by which educators could refine the intellectual tools students use to make sense of the incomplete, often pseudoscientific evidence they encounter everywhere but particularly on various social media.

References

Adams, J. P., & Slater, T. F. (2000). Astronomy in the *National Science Education Standards*. *Journal of Geoscience Education*, *48*(1), 39–45. https://doi.org/10.5408/1089-9995-48.1.39

Aljaafreh, A., & Lantolf, J. P. (1994). Negative Feedback as Regulation and Second Language Learning in the Zone of Proximal Development. *The Modern Language Journal*, *78*(4), 465–483. https://doi.org/10.1111/j.1540-4781.1994.tb02064.x

Anderson, L. W., & Burns, R. B. (1990). The Role of Conceptual Frameworks in Understanding and Using Classroom Research. *South Pacific Journal of Teacher Education*, *18*(1), 5–18. https://doi.org/10.1080/0311213900180102

Barzilai, S., & Chinn, C. A. (2018). On the Goals of Epistemic Education: Promoting Apt Epistemic Performance. *Journal of the Learning Sciences*, *27*(3), 353–389. https://doi.org/10.1080/10508406.2017.1392968

Barzilai, S., & Chinn, C. A. (2020). A review of educational responses to the “post-truth” condition: Four lenses on “post-truth” problems. *Educational Psychologist*, *55*(3), 107–119. https://doi.org/10.1080/00461520.2020.1786388

Challenger, A., Sumner, P., & Bott, L. (2022). COVID-19 myth-busting: An experimental study. *BMC Public Health*, *22*(1), 131. https://doi.org/10.1186/s12889-021-12464-3

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education*, *86*(2), 175–218. https://doi.org/10.1002/sce.10001

Clark, D. B., Nelson, B. C., Chang, H.-Y., Martinez-Garza, M., Slack, K., & D'Angelo, C. M. (2011). Exploring Newtonian mechanics in a conceptually-integrated digital game: Comparison of learning and affective outcomes for students in Taiwan and the United States. *Computers & Education*, *57*(3), 2178–2195. https://doi.org/10.1016/j.compedu.2011.05.007

Coffin, J. M., & Fan, H. (2016). The Discovery of Reverse Transcriptase. *Annual Review of Virology*, *3*(1), 29–51. https://doi.org/10.1146/annurev-virology-110615-035556

Compton, J., Van Der Linden, S., Cook, J., & Basol, M. (2021). Inoculation theory in the post-truth era: Extant findings and new frontiers for contested science, misinformation, and conspiracy theories. *Social and Personality Psychology Compass*, *15*(6), e12602. https://doi.org/10.1111/spc3.12602

Cook, J., Lewandowsky, S., & Ecker, U. K. H. (2017). Neutralizing misinformation through inoculation: Exposing misleading argumentation techniques reduces their influence. *PLOS ONE*, *12*(5), e0175799. https://doi.org/10.1371/journal.pone.0175799

diSessa, A. A. (2014). A History of Conceptual Change Research: Threads and Fault Lines. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (2nd ed., pp. 88–108). Cambridge University Press. https://doi.org/10.1017/CBO9781139519526.007

Doja, A., & Roberts, W. (2006). Immunization and Autism: A review of the Literature. *The Canadian Journal of Neurological Sciences*, *33*, 341–346.

Donnelly, J. (2006). The intellectual positioning of science in the curriculum, and its relationship to reform. *Journal of Curriculum Studies*, *38*(6), 623–640. https://doi.org/10.1080/00220270600822228

Druckman, J. N., & McGrath, M. C. (2019). The evidence for motivated reasoning in climate change preference formation. *Nature Climate Change*, *9*(2), 111–119. https://doi.org/10.1038/s41558-018-0360-1

Duncan, R. G., Chinn, C. A., & Barzilai, S. (2018). Grasp of evidence: Problematizing and expanding the next generation science standards' conceptualization of evidence. *Journal of Research in Science Teaching*, *55*(7), 907–937. https://doi.org/10.1002/tea.21468

Duschl, R. (2008). Science Education in Three-Part Harmony: Balancing Conceptual, Epistemic, and Social Learning Goals. *Review of Research in Education*, *32*(1), 268–291. https://doi.org/10.3102/0091732X07309371

Feinstein, N. (2011). Salvaging science literacy. *Science Education*, *95*(1), 168–185. https://doi.org/10.1002/sce.20414

Fortner, R. W., & Meyer, R. L. (2000). Discrepancies Among Teachers' Priorities for and Knowledge of Freshwater Topics. *The Journal of Environmental Education*, *31*(4), 51–53. https://doi.org/10.1080/00958960009598652

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Furtak, E. M., Hardy, I., Beinbrech, C., Shavelson, R. J., & Shemwell, J. T. (2010). A Framework for Analyzing Evidence-Based Reasoning in Science Classroom Discourse. *Educational Assessment*, *15*(3–4), 175–196. https://doi.org/10.1080/10627197.2010.530553

Gabis, L. V., Attia, O. L., Goldman, M., Barak, N., Tefera, P., Shefer, S., Shaham, M., & Lerman-Sagie, T. (2022). The myth of vaccination and autism spectrum. *European Journal of Paediatric Neurology*, *36*, 151–158. https://doi.org/10.1016/j.ejpn.2021.12.011

Goel, V. (2007). Anatomy of deductive reasoning. *Trends in Cognitive Sciences*, *11*(10), 435–441. https://doi.org/10.1016/j.tics.2007.09.003

Greene, J. A., & Yu, S. B. (2016). Educating Critical Thinkers: The Role of Epistemic Cognition. *Policy Insights from the Behavioral and Brain Sciences*, *3*(1), 45–53. https://doi.org/10.1177/2372732215622223

Hattie, J., & Yates, G. (2014). *Visible learning and the science of how we learn*. Routledge, Taylor & Francis Group.

Hewson, P. W. (1981). A Conceptual Change Approach to Learning Science. *European Journal of Science Education*, *3*(4), 383–396. https://doi.org/10.1080/0140528810304004

Hofer, B. K., & Pintrich, P. R. (1997). The Development of Epistemological Theories: Beliefs About Knowledge and Knowing and Their Relation to Learning. *Review of Educational Research*, *67*(1), 88–140. https://doi.org/10.3102/00346543067001088

Hughes, S. (2019). Demystifying Theoretical and Conceptual Frameworks: A Guide for Students and Advisors of Educational Research. *JOURNAL OF SOCIAL SCIENCES*, *58*(1–3). https://doi.org/10.31901/24566756.2019/58.1-3.2188

Ivanov, B., Parker, K. A., & Dillingham, L. (2020). Inoculation Theory as a Strategic Tool. In H. D. O'Hair & M. J. O'Hair (Eds.), *The Handbook of Applied Communication Research* (1st ed., pp. 11–28). Wiley. https://doi.org/10.1002/9781119399926.ch1

Johnson, A., & Madsen, J. K. (2024). Inoculation hesitancy: An exploration of challenges in scaling inoculation theory. *Royal Society Open Science*, *11*(6), 231711. https://doi.org/10.1098/rsos.231711

Kelly, T. (2008). Evidence: Fundamental Concepts and the Phenomenal Conception. *Philosophy Compass*, *3*(5), 933–955. https://doi.org/10.1111/j.1747-9991.2008.00160.x

Keren, A. (2018). The Public Understanding of What? Laypersons' Epistemic Needs, the Division of Cognitive Labor, and the Demarcation of Science. *Philosophy of Science*, *85*(5), 781–792. https://doi.org/10.1086/699690

Kneupper, C. W. (1978). Teaching Argument: An Introduction to the Toulmin Model. *College Composition & Communication*, *29*(3), 237–241. https://doi.org/10.58680/ccc197816301

Kozulin, A. (1995). The Learning Process: Vygotsky's Theory in the Mirror of its Interpretations. *School Psychology International*, *16*(2), 117–129. https://doi.org/10.1177/0143034395162003

Larkin, M. J. (2001). Providing Support for Student Independence through Scaffolded Instruction. *TEACHING Exceptional Children*, *34*(1), 30–34. https://doi.org/10.1177/004005990103400104

Le Grice, S. F. J. (2012). Human Immunodeficiency Virus Reverse Transcriptase: 25 Years of Research, Drug Discovery, and Promise. *Journal of Biological Chemistry*, *287*(49), 40850–40857. https://doi.org/10.1074/jbc.R112.389056

Marginson, S. (1999). After globalization: Emerging politics of education. *Journal of Education Policy*, *14*(1), 19–31. https://doi.org/10.1080/026809399286477

Maxwell, J. A. (2013). *Qualitative research design: An interactive approach* (3rd ed). SAGE Publications.

Mayer, R. E., Stull, A., DeLeeuw, K., Almeroth, K., Bimber, B., Chun, D., Bulger, M., Campbell, J., Knight, A., & Zhang, H. (2009). Clickers in college classrooms: Fostering learning with questioning methods in large lecture classes. *Contemporary Educational Psychology*, *34*(1), 51–57. https://doi.org/10.1016/j.cedpsych.2008.04.002

Moreno, R., & Mayer, R. (2007). Interactive Multimodal Learning Environments: Special Issue on Interactive Learning Environments: Contemporary Issues and Trends. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (p. 13165). National Academies Press. https://doi.org/10.17226/13165

Next Generation Science Standards: For States, By States (p. 18290). (2013). National Academies Press. https://doi.org/10.17226/18290

Nussbaum, E. M. (2011). Argumentation, Dialogue Theory, and Probability Modeling: Alternative Frameworks for Argumentation Research in Education. *Educational Psychologist*, *46*(2), 84–106. https://doi.org/10.1080/00461520.2011.558816

Nussbaum, E. M., & Edwards, O. V. (2011). Critical Questions and Argument Stratagems: A Framework for Enhancing and Analyzing Students' Reasoning Practices. *Journal of the Learning Sciences*, *20*(3), 443–488. https://doi.org/10.1080/10508406.2011.564567

Pennycook, G., & Rand, D. G. (2019). Lazy, not biased: Susceptibility to partisan fake news is better explained by lack of reasoning than by motivated reasoning. *Cognition*, *188*, 39–50. https://doi.org/10.1016/j.cognition.2018.06.011

Journal of Studies in Education
ISSN 2162-6952
2024, Vol. 14, No. 4

Pinker, S. (2021). *Rationality: What it is, why it seems scarce, why it matters* (First edition). Viking.

Pollock, J. L. (1987). Defeasible Reasoning. *Cognitive Science*, *11*(4), 481–518. https://doi.org/10.1207/s15516709cog1104_4

Rapanta, C., & Christodoulou, A. (2022). Walton's types of argumentation dialogues as classroom discourse sequences. *Learning, Culture and Social Interaction*, *36*, 100352. https://doi.org/10.1016/j.lcsi.2019.100352

Reiser, B. J. (2004). Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work. *Journal of the Learning Sciences*, *13*(3), 273–304. https://doi.org/10.1207/s15327809jls1303_2

Reiser, B. J., & Tabak, I. (2014). Scaffolding. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (2nd ed., pp. 44–62). Cambridge University Press. https://doi.org/10.1017/CBO9781139519526.005

Rudolph, J. L. (2002). *Scientists in the classroom: The cold war reconstruction of American science education*. Palgave.

Ruhrmann, G., Guenther, L., Kessler, S. H., & Milde, J. (2015). Frames of scientific evidence: How journalists represent the (un)certainty of molecular medicine in science television programs. *Public Understanding of Science*, *24*(6), 681–696. https://doi.org/10.1177/0963662513510643

Samarapungavan, A. (2018). *Construing Scientific Evidence: The Role of Disciplinary Knowledge in Reasoning with and About Evidence in Scientific Practice* (pp. 55–76). Routledge.

Shen, J., & Confrey, J. (2010). Justifying Alternative Models in Learning Astronomy: A study of K–8 science teachers' understanding of frames of reference. *International Journal of Science Education*, *32*(1), 1–29. https://doi.org/10.1080/09500690802412449

Shepardson, D. P. (1999). Learning science in a first grade science activity: A Vygotskian perspective. *Science Education*, *83*(5), 621–638. https://doi.org/10.1002/(SICI)1098-237X(199909)83:5<621::AID-SCE7>3.0.CO;2-T

Sinatra, G. M., Kienhues, D., & Hofer, B. K. (2014). Addressing Challenges to Public Understanding of Science: Epistemic Cognition, Motivated Reasoning, and Conceptual Change. *Educational Psychologist*, *49*(2), 123–138. https://doi.org/10.1080/00461520.2014.916216

Smagorinsky, P. H. (2009). The Culture of Vygotsky. *Reading Research Quarterly*, *44*(1), 85–95. https://doi.org/10.1598/RRQ.44.1.4

Spada, N., & Lightbown, P. M. (1993). Instruction and the Development of Questions in L2 Classrooms. *Studies in Second Language Acquisition*, *15*(2), 205–224. https://doi.org/10.1017/S0272263100011967

Swain, M. (1974). French Immersion Programs Across Canada: Research Findings. *The Canadian Modern Language Review*, *31*(2), 117–129. https://doi.org/10.3138/cmlr.31.2.117

Swain, M., & Lapkin, S. (1989). Canadian Immersion and Adult Second Language Teaching: What's the Connection? *The Modern Language Journal*, *73*(2), 150–159. https://doi.org/10.1111/j.1540-4781.1989.tb02537.x

Vogel-Walcutt, J. J., Gebrim, J. B., Bowers, C., Carper, T. M., & Nicholson, D. (2011). Cognitive load theory vs. constructivist approaches: Which best leads to efficient, deep learning?: CLT vs. constructivism for learning. *Journal of Computer Assisted Learning*, *27*(2), 133–145. https://doi.org/10.1111/j.1365-2729.2010.00381.x

Walton, D. (2006). Examination dialogue: An argumentation framework for critically questioning an expert opinion. *Journal of Pragmatics*, *38*(5), 745–777. https://doi.org/10.1016/j.pragma.2005.01.016

Winn, J. A. (1994). Promises and Challenges of Scaffolded Instruction. *Learning Disability Quarterly*, *17*(1), 89–104. https://doi.org/10.2307/1511107

Zohar, A., & David, A. B. (2008). Explicit teaching of meta-strategic knowledge in authentic classroom situations. *Metacognition and Learning*, *3*(1), 59–82. https://doi.org/10.1007/s11409-007-9019-4