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TEACHING ABOUT THE ROLE OF AESTHETICS IN SCIENCE THROUGH A SHORT STORY BASED ON THE HISTORY OF THE CONCEPT OF ENERGY

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Abstract

The nature of science or, briefly, what science is and how it works, is an essential component of science education. However, it is not typically well understood by neither teachers nor students in K-12 settings. In particular, the complex role of aesthetics, i.e., of experiences of beauty, emotions, and taste, on how scientists engage with the practices and products of science is often misunderstood as being non-existent, or at least ideally so. This misconception has a negative effect on many students' attitudes towards science, which, in turn, can negatively affect their learning of science.

In response to these concerns, the present study addresses the development and implementation, as well as the assessment of the effects, of an intervention that aimed at improving pre-service elementary teachers' attitudes towards science by fostering an enhanced understanding of the role of aesthetics in science. The intervention was based on a short story concerned with episodes from the historical development of the concept of energy. It highlights ideas about the role of aesthetics in science through the events narrated in the story and through explicit statements and questions that foster personal reflection about these ideas. The discussion of this story formed the basis of an activity that was performed as part of one lesson in an introductory science methods course.

To assess the effects of the intervention on the participants' attitudes towards science and understanding of the role of aesthetics in science, survey data was collected before and after the intervention and analyzed using a mixed-methods approach. Additionally, a small number of confirmatory follow-up interviews were performed and used to assess the accuracy of the analysis. The results show a positive effect of the intervention on the attitudes towards science of all the pre-service teachers that participated in the study. Moreover, the results also show a positive, though moderate, improvement in their understanding of the role of aesthetics in science. However, the improvement was not uniform among the three elements of aesthetics, being greatest for the role of emotions and smallest for the role of taste.

Teaching about the role of aesthetics in science through a short story based on the history of the concept of energy

Understanding the nature of science (NOS), i.e. “how scientists work and engage with each other and society, how science answers questions, and how [science] generates knowledge about nature” (McComas and Clough, 2020, pp.5), is widely accepted as an essential component of science education (N. G. Lederman, 2007; N. G. Lederman and Lederman, 2014; McComas, 2020b; McComas and Clough, 2020), and highlighted as an important goal in documents such as the Framework for K-12 Science Education (National Research Council, 2012) and the Next Generation Science Standards (National Research Council, 2013). A wide body of literature addresses the rationale for including NOS instruction in K-12 science classrooms (e.g. N. G. Lederman, 2007; N. G. Lederman and Lederman, 2014; McComas, 2020b; National Research Council, 2012), which is clearly summarized by the following statement by Matthews (2014):

> If students do not learn and appreciate something about science— its history, its interrelations with culture, religion, worldviews, and commerce, its philosophical and metaphysical assumptions, its epistemology and methodology —then the opportunity for science to enrich culture and human lives is correspondingly minimised (p.1)

More specific arguments include the idea that understanding NOS is necessary for understanding science itself, that it nurtures interest and appreciation for science, and that it is necessary for taking informed citizenship decisions on a wide range of socio-scientific issues with potentially large impact on people’s lives (McComas, 2020b).

However, research shows that K-12 students and teachers typically lack an accurate understanding of NOS (see e.g. Cofré et al., 2019; N. G. Lederman, 2007; N. G. Lederman and Lederman, 2014; McComas and Clough, 2020 for reviews). In particular, science is widely perceived as a linear and stepwise activity with no room for creativity or aesthetics

—the latter of which encompasses experiences of beauty, emotions, and taste (Wickman, 2006). Rather, creativity and aesthetics are generally assumed to be confined to the arts (see e.g. Braund and Reiss, 2019; Flannery, 1991, 1992; Girod et al., 2003; McComas, 2020b; McLeish, 2019; Wickman, 2006), even if ample evidence shows that they play a fundamental role in the practice and products of science (Chandrasekhar, 1989; Dirac, 1963; Flannery, 1991 & 1992, Feynman and Leighton, 2001 & 2005, Girod, 2007; McLeish, 2019; Poincaré, 1920; Root-Bernstein, 1996; Tauber, 1996; Wickman, 2006). Said evidence includes many personal accounts by renowned scientists, such as the threoretical physicist and mathematician Henri Poincaré (1920), who stated that the scientist does not study science because it is useful to do so. He studies it because he takes pleasure in it, and he takes pleasure in it because it is beautiful (p.20). Unfortunately, this aspect of science is often misunderstood among non-scientists, an issue that undermines many students' and teachers' attitudes towards science (Braund and Reiss, 2019; Girod et al., 2003; McComas, 2020b; McLeish, 2019; Wickman, 2006).

Poor attitudes towards science are an important issue in the context of science education (Tytler, 2014). While the term attitudes is not unambiguously defined, and is largely understood as referring to a wide array of interrelated constructs such as interest and values, it is broadly accepted that attitudes are related to motivation and that they can affect students' orientation to learn and, accordingly, their learning achievement (see e.g. Koballa and Glynn, 2013; Tytler, 2014, and references therein). Accordingly, it is important to address misconceptions about NOS, particularly those pertaining to creativity and aesthetics that may negatively affect science learning by fostering negative attitudes towards science and/or school science among teachers and students.

Nevertheless, the role of aesthetics in science is rarely addressed in the context of science education (Bellocchi et al., 2017), particularly in the context of NOS. However, an extensive body of research has addressed the question of how to effectively teach other aspects of NOS (see Cofré et al., 2019; Khishfe, 2023; N. G. Lederman, 2007; McComas et al., 2020 for reviews). One of several effective approaches supported by said research is using the history of science (HOS) as a means to reveal how science works and, in particular to reveal science as a “human endeavor” (McComas, 2020c). Moreover, besides being an effective means to improve understanding of NOS, strategies based on HOS have been shown to be effective at improving students’ attitudes towards science (e.g. Clough et al., 2010; Hong and Lin-Siegler, 2012; Lin et al., 2011).

The present study concerns an intervention geared towards pre-service elementary teachers (PSTs), with the goal of enhancing their attitudes towards science by fostering their NOS understanding, specifically regarding the role of aesthetics in science. The intervention was based on a short story that gathers episodes from the historical development of the concept of energy and highlights NOS ideas about aesthetics through explicit comments and questions, meant to foster the reader’s personal reflection about these ideas. The discussion of this story formed the basis of an activity that was performed as part of an introductory science methods course. The effects of the intervention were assessed using a mixed-methods approach based on pre- and post-intervention survey data and confirmatory interviews.

The details of the study are presented in the following chapters, starting with a brief review of current research literature on NOS teaching practices, particularly those that use HOS as a context for NOS ideas, and how the role of aesthetics in science is addressed in the science education literature. This is followed by the theoretical framework of the study, which includes a detailed description of aesthetics and its relationship to scientific practices, together with a description of the attitudinal constructs relevant to the study. Then, the purpose of the study and the research questions that guide it are described and followed by a detailed account of the methods used to pursue those questions. Finally, the results of the study are presented and then discussed, together with the limitations and implications of the study.

Literature Review

Teaching NOS

A large body of research has focused on identifying the best practices for teaching NOS, from which McComas et al. (2020) identified three essential characteristics of effective NOS instruction: (1) In the first place, effective NOS instruction needs to explicitly focus attention on NOS ideas, making it clear to students that these are an essential part of the content they should strive to understand. In particular because existing misconceptions about NOS are unlikely to be dispelled without explicit instruction that facilitates the necessary conceptual change. (2) In the second place, effective NOS instruction needs to engage students in personal reflection about NOS ideas, providing students with opportunities to analyze the science content they are learning within the framework of NOS and to establish connections between their own activities in the science classroom and the activities of scientists at work. (3) Finally, effective NOS instruction needs to be contextualized within science content and instruction for students to relate it to authentic scientific ideas, the processes involved in doing science, and the final products of scientific work, so that they can come to understand these as essential aspects of science that they need to engage with.

Naturally, as important as how best to teach NOS, it is essential to determine *which* NOS ideas are the most important and accessible to teachers and students, a question about which there is no unanimous agreement (N. G. Lederman and Lederman, 2014; McComas, 2020b). Some authors advocate for a *family relations* approach (Irzik and Nola, 2011) that attempts to avoid generalizations that may obscure, or even mislead about, the fundamental differences that exist among scientific disciplines, arguing instead for four open-ended categories of special importance: processes of inquiry, aims and values, methods, and products. Nonetheless, the most frequent approach is the *consensus view* of NOS, consisting of nine key elements or aspects that address common, but fundamental, misconceptions held by students and teachers alike (McComas, 2020b). McComas classified these key aspects into three categories: (a) tools, processes, and products of science; (b) the domain of science and its limitations; and (c) the human elements of science. The first and second category include ideas such as the fundamental role played by evidence in science, that several shared methods are common across scientific disciplines but no single, stepwise "scientific method" exists, and that science is tentative, durable, and self-correcting. The role of creativity and subjectivity in science, as well as the natural feedback between science, society, and culture, are included in the third category, i.e., the human elements of science. Additionally, some authors have noted the emphasis given by the consensus view to *epistemic* aspects of NOS while disregarding *non-epistemic* aspects such as the social structures of science, including the nature of scientific communication, the processes involved in the validation of new knowledge, and the ethics of scientific research (García-Carmona, 2024), as well as the professional relationships among scientists and the impact of large social and economical structures on scientific research (Aragón-Méndez et al., 2019).

The ideas within the categories of any of these approaches are not completely independent (Osborne et al., 2001, 2003). For example, regarding creativity in science, McComas (2020b) highlighted how the “myth of the stepwise scientific method” leads students to believe science is a formulaic activity that is “nothing like the making of art, for instance” (p. 53). Analogously, the role of subjectivity in science cannot be fully appreciated without understanding how scientific ideas are communicated and evaluated by the scientific community, which underlies the tentative and self-correcting nature of science. Moreover, Ozgelen et al. (2013) found that activities that emphasized this interrelatedness by fostering personal reflection about the connections between individual key aspects of NOS improved PSTs’ ability to integrate their NOS understanding into a meaningful, overarching framework.

On the other hand, multiple empirical studies have found that some NOS aspects seem more difficult to learn than others (Cofré et al., 2019): with creativity among the easiest, tentativeness and socio-cultural-embededness among the most difficult, and mixed results for subjectivity. The reasons for these patterns are not yet clear but some authors have suggested they may be associated to the methodologies and context of instruction, or to learners' traits, such as personal motivations of worldviews (Mesci, 2020; Mesci and Schwartz, 2017; Valencia Narbona et al., 2023). What is clear is that teachers and students largely lack a robust understanding of most aspects of NOS (Cofré et al., 2019; N. G. Lederman and Lederman, 2014; McComas, 2020b) and that this lack of understanding can have an detrimental effect on their attitudes towards science (McComas, 2020b). In particular, several authors (Flannery, 1991, 1992; McComas, 2020b; McLeish, 2019; Wickman, 2006; Wong and Hodson, 2009) have addressed the danger of students choosing not to pursue learning about science due to a lack of understanding of the human aspects of science, such as creativity and subjectivity.

To address this situation, many different approaches to NOS instruction have been developed that suit the above mentioned characteristics of effective NOS instruction and are adapted to students and teachers in different educational contexts (see Cofré et al., 2019; Khishfe, 2023; McComas et al., 2020 for reviews). Among these, one prominent strategy is to use HOS as context to explicitly address different aspects of NOS in the context of actual scientific developments, with positive results fostering understanding of these aspects (Khishfe, 2023; McComas, 2020c). Moreover, some authors have argued that since HOS "reveals science as a 'human endeavor" (McComas, 2020c, p.527), it has the potential to increase students' interest and motivation to learn science. In fact, Hong & Lin-Siegler (2012) also found increased interest in science, as well as improved performance in problem solving activities, as the result of an intervention where they included biographical and background information from the work of scientists that highlighted their struggles. They attributed these effects to the idea that portraying scientists as normal human beings, who struggle and fail, makes them more relatable to students than accounts that only address their achievements, allowing for the establishment of an affective connection that promotes interest and more effective learning. On the other hand, Clough et al. (2010) created a set of historical short stories which they implemented in an undergraduate college biology course. The stories contained embedded questions and comments that prompted students' explicit reflection on various NOS ideas, including the role of creativity in science. Students read the stories on their own and had brief discussions about them in class. As a result of this intervention, Clough et al. (2010) found that most students' reported an increased interest in science, in general, and in the content of the stories, in particular. They saw smaller, but positive, gains in their interest in science careers. Moreover, Clough et al. found a significant improvement in students' NOS understanding. However, while these and many other studies have addressed the human elements of science with positive results, few address the role played by aesthetics in science.

Aesthetics and the NOS Framework

Aesthetics—understood as experiences of beauty, emotions, and taste—is not typically associated with science in the context of K-12 schools and beyond, even if it is an unavoidable aspect of science (see e.g. Flannery, 1991, 1992; Wickman, 2006; Wickman et al., 2022 and the Theoretical Framework section for further discussion).

Though aesthetics fits well within what is known in the consensus view of NOS as the human elements of science (McComas, 2020b), it is rarely included as a separate aspect of NOS. Even the subjectivity aspect is actually focused on the idea that science is theory-ladden, i.e., that scientists "theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work" (N. G. Lederman, 2007, p.834). Some authors, when describing this aspect of NOS from the perspective of the consensus view, emphasize that scientists may have biases that affect their research in various ways and how science "makes use of intersubjectivity that tends to cancel out any biases held by [individuals] thus minimizing negative impacts of theory-based observation" (McComas, 2020b, p.55). Others (e.g. Mesci and Schwartz, 2017) identify scientists' "values, knowledge, and prior experiences" (p.2) as *personal subjectivity* and distinct from the theory-ladenness of science, understood then as how currently accepted knowledge affects the collection and interpretation of evidence. But few authors, in this context, address scientists personal feelings and emotions in response to the subjects and practices of their work and how these can affect their research, including how they can affect their motivations to do science, or how their personal taste can influence theory-choice or even the subjects that become the focus of research. And while some authors have recently highlighted the importance of embracing a broader view of NOS that emphasizes social and cultural aspects of science (e.g. Aragón-Méndez et al., 2019; Cobo et al., 2022; Galili, 2019; Gandolfi, 2021; García-Carmona, 2024), they leave out scientists' personal experiences of beauty, emotions, and taste.

Instruments commonly used to assess NOS understanding largely ignore aesthetic aspects of science as well. For example, the VNOS (Views of Nature of Science Questionnaire) (N. G. Lederman et al., 2002) in its multiple versions and the SUSSI (Student Understanding of Science and Scientific Inquiry) (Liang et al., 2006), two of the most frequently used instruments (McComas et al., 2020) are largely in line with the consensus view of NOS. Thus, as described above, they address subjectivity with a focus of the theory-ladenness of science while ignoring aesthetic aspects. A notable exception is the Views on Science-Technology-Society (VOSTS) instrument (Aikenhead and Ryan, 1992), which includes a question addressing whether choices made by scientists as part of their work may be affected by their "inner feelings, upon the personal way a scientist views a theory, or upon personal gains such as fame, job security or money", and others where it addresses whether this is different between female and male scientists. It also addresses scientists' motivations to work hard and includes their personal curiosity and enjoyment among the plausible, but not preferred, answers. However, empirical studies that emphasize these items are rare.

Aesthetics in Other Science Education Frameworks

Even if aesthetics is largely absent from NOS frameworks, several authors have advocated for its inclusion in science education (e.g. Flannery, 1991, 1992, McLeish, 2019) and developed frameworks and interventions guided by that goal (e.g. Girod, 2007; Girod et al., 2003; Hong and Lin-Siegler, 2012; Jaber and Hammer, 2016; Pugh and Girod, 2007; Wickman, 2006). For example, Girod (2007), argued that science education should draw from the sense of beauty in the enhanced experience of the world afforded by scientific knowledge, and linked this idea to Dewey's (1934) concept of an aesthetic experience, which he described as an experience with a series of qualities that include "(i) the fusion (...) of thought, emotion, and action; (ii) the expansion of one's perception (...), and; (iii) an increased sense of value for this newfound perspective" (p.48).

Some authors (Girod et al., 2003; Pugh and Girod, 2007) argue that science teaching should focus on aesthetic understanding, i.e. a "rich network of conceptual knowledge combined with a deep appreciation for the beauty and power of ideas that literally transforms one's experiences and perceptions of the world" (pp. 577-578). Girod et al. (2003) went on to argue that teaching and learning should foster aesthetic understanding by providing opportunities for students to have meaningful experiences that connect them to the world and to science through the arts. Their teaching strategies are based on what they have called *artistically crafting pedagogy*, i.e., reanimating content ideas in artful and compelling ways, providing authentic opportunities for students to explore content ideas, re-seeing the world by paying attention to details within the context of new knowledge, modeling a variety of ways of engaging in reflective practices around content, and nurturing students' explorations as their understanding grows.

Girod et al. (2003) tested the effect of their approach on two groups of 4th graders through a unit on geology. Only one group experienced the experimental treatment. The experimental unit was focused around the idea that rocks tell stories that can be uncovered using knowledge about geology. As a measure, they used a survey that asked students to match their experiences to an ideal situation of aesthetic understanding, as well as follow up interviews. They found that most students in the experimental group had experiences that had elements of aesthetic understanding, i.e., they were emotional and they enhanced the value of the content, as well as the associations that students established between the given content, other content, and their daily activities outside of school. In a later study, Lin et al. (2011) tested the effects of an intervention based on the the idea of integrating the principles of aesthetic understanding with reflective inquiry. The authors tested their intervention on two groups of 8th graders, with only one group experiencing the intervention. The intervention was centered around Bernoulli's principle. It included sharing of feelings of awe by the teacher in response to a video showing seeds in flight, pre-designed hands-on experiments, an inquiry activity led by students, discussions that explicitly addressed connections to engineering and technology by establishing parallels between seeds and gyrocopters, and finally an activity where students where asked to write a poem or short statement to describe their feelings in response to the video of the seeds in flight. The authors performed pre- and post-intervention content knowledge tests, as well as qualitative data analysis of classroom observations, students responses to the assignments, and interviews. They concluded that the intervention improved students' content knowledge acquisition with respect to the control group, as well as students' attitudes toward science learning.

It is important to highlight that, while these approaches address scientific ideas in the context where they arise and aim at fostering experiences that allow students to "feel like a scientist" (Jaber and Hammer, 2016), they do not explicitly address these ideas as characteristic of science and it is unclear whether students do associate them with science in general. Similarly, a vast array of studies have used arts integration in the science classroom as a means to foster engagement with science content, with promising results in terms of attitudes towards science courses and academic achievement (e.g. Graham and Brouillette, 2016; Güney and Şeker, 2017; Ooms et al., 2018; Shanahan and Nieswandt, 2009). However, these strategies generally do not target what science is and how it is done and there is no clear evidence that they are thinking about the role of aesthetics when it comes to science beyond their classroom.

Theoretical Framework

Aesthetics

The Oxford English Dictionary (n.d.) defines aesthetics as "a set of principles concerned with the nature and appreciation of beauty, especially in art." However, that is not the only meaning of the term. Following Wickman et al. (2022), in this study aesthetics will refer to an individual's experiences of beauty, emotions, and taste, regardless of the context where these are manifested, though the focus will be on scientific contexts.

Just as the term aesthetics is often associated to the arts, there is a common misconception that there exists a dichotomy between science, associated to reason, and art and aesthetics, associated to beauty (see e.g. Flannery, 1991; McLeish, 2019; Snow, 1959; Tauber, 1996; Wickman, 2006). According to Wickman (2006), the pervasiveness of this misconception may be explained, at least partially, by considering the evolution of the term *aesthetics*. In fact, the term aesthetics was introduced in the eighteenth century by philosopher Alexander Baumgarten to refer to knowledge that arises from the senses and to the perception of beauty, particularly in the arts (Goldman, 2005). Kant broadened the concept to include both experiences of pleasure (or displeasure) and judgments qualifying such experiences, which include, but are not limited to, assessments of what is perceived as beautiful in the arts and in nature (Goldman, 2005; Wickman, 2006). Notably, Kant also established a clear distinction between this kind of judgment and what he called pure and practical reason, i.e., cognition, morality and values, and action. The most common meaning of the term today is largely inspired by the work of Hegel, who used the term as limited to describe beauty, specifically in the arts (Wickman, 2006).

Flannery (1992), on the other hand, accounted for this false dichotomy by pointing out that the aesthetic and creative are among the *private aspects of science* that are largely inaccessible to non-scientists, while the public aspects, those reflected in scientific publications and other media representations of science, do not discuss the subjective activities that drive the process of science and, rather, present a succinct and objective account of the final products of those processes. This was addressed by Wickman (2006) as "the fallacy of confusing the practice with the product", adding that:

> Few people would deny the necessity of aesthetic understanding in either composing or performing music. Nevertheless, just as scientific results can be repeated from what is written in a report, a musical piece can be repeated over again from its score, although aesthetics is nowhere mentioned in either of these scripts. (p.14)

Regardless of the origin of this misconception, a closer examination of the elements of aesthetics in relation to the practices of science reveals a close and unavoidable connection, as I will argue in what follows.

Beauty, Emotion, and Taste as Elements of NOS

Notable physicist, and winner of the Nobel Prize in Physics in 1983, Subrahmanyan Chandrasekhar (1989) used personal and historical accounts by other great scientists and mathematicians to show that many scientists are motivated by the perceived beauty of nature and by the pursuit of beauty in their own and their fellow scientists' work. For Chandrasekhar, the concept of beauty retains its common meaning (e.g., the aesthetic appeal of the night sky) but it includes as well more abstract meanings derived from scientific and mathematical knowledge, such as the simplicity of an experiment, a theory's power to synthesize previously disconnected ideas, or the perceived beauty in the symmetry of an equation used to describe a physical phenomenon. Similarly, Flannery (1991) highlighted order as a "central aesthetic quality in science" (p.581), underlying the aesthetic qualities of patterns, rhythm, form, and hierarchies. She also addressed the sense of beauty to be found in the contrast between simplicity and complexity and, even more so, in the act of finding order amidst chaos. In that sense, she argues, scientists' experiences of beauty are not limited to the intrinsic beauty of their objects of study. On one hand, the beauty of nature is enriched by its interpretation through the lens of scientific knowledge. Just like scientists observations and their interpretations of evidence, their experiences of beauty are thus unavoidably theory-ladden. On the other, the practices and products of science can be perceived as beautiful too, as exemplified in Chandrasekhar's passionate account of General Relativity as "probably the most beautiful of all existing theories" (Chandrasekhar, 1984).

Accordingly, the experience of beauty in nature is perceived by some scientists as being enhanced by the scientific approach (see e.g. Feynman, 2005, p.11). However, many assume that the analytical approach of science obliterates the beauty otherwise perceived in objects of nature, possibly because said analytical approach is often inaccessible to non-specialists as it is, like the perception of its beauty, founded on a vast body of previous scientific, and often mathematical, knowledge (McLeish, 2019; Wickman, 2006).

Intense experiences of beauty are just some of the arguments for the abundant emotional accounts of science that appear in prominent scientists' testimony and biographical accounts (Chandrasekhar, 1989; Dirac, 1963; Feynman, 2005; Feynman and Leighton, 2001; Poincaré, 1920; Taber, 1997). Another one is interest, as in the following statement by another theoretical physicist and Nobel Prize winner, Richard P. Feynman (Feynman, 2005):

> The same thrill, the same awe and mystery, comes again and again when we look at any question deeply enough. With more knowledge comes a deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer might prove disappointing, with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries, certainly a grand adventure! (p.243)

Feynman's quote is an example of the intense emotions that can be elicited by curiosity and interest during scientific research. As emphasized by Wickman (2006), human interest is the fundamental driver of science. Not only because interest drives scientists motivation to work on scientific issues but also because science is not a projection of reality (p.10).

Science is socially constructed by a community of scientists that selects what objects, questions, and solutions are deemed interesting. This is naturally affected by the previous experiences and knowledge of scientists, as highlighted by consensus view of NOS as the theory-laddeness of observations or the subjective aspect of science (McComas, 2020a, 2020b). However, the role of subjectivity in science is multifaceted, interest in science is also affected by the personal taste of scientists, just as with any other human activity (Wickman, 2006). Instances of this abound in the history of science, some of which are described in the historical story developed for the present study (Appendix C).

Naturally, scientists are not driven only by interest or beauty, scientists are human and their motivations cannot be assumed to be uniform. However, precisely because they are human, it is hard to envision they would not be driven to some extent by aesthetic experiences and personal values. Moreover, scientists have lives outside of their work that may inevitably affect their choices of what to study, where, and how, with inevitable effects on the scientific knowledge that is generated (Wickman, 2006). And while these effects might be serendipitous, that does not mean that their impact is irrelevant. In fact, that choices about what is studied and how are made by humans, and often based on a multitude of factors that may be serendipitous, socio-cultural, and also aesthetic, such as what is perceived as beautiful, is an important notion for NOS education, directly related to key aspects of NOS such as tentativeness and socio-cultural embeddedness (McComas, 2020b) that have been shown to be among the hardest to learn for teachers and students alike (Cofré et al., 2019).

Ignoring these facts promotes the misconception that science only deals with problems that have a single solution and that there is no room for subjectivity in science (McComas, 2020b). Moreover, focusing exclusively on theory-ladenness and ignoring the role of personal taste and emotions in science can erode the perception of science as a human endeavour and promote negative attitudes towards science (Flannery, 1991, 1992; Girod, 2007; McLeish, 2019; Wickman, 2006).

In view of this complex scenario, for the limited scope of the present study an appropriately "accurate" or "sophisticated" understanding of the role of aesthetics in science will be one that recognizes that: (a) Scientists have experiences of beauty as a result of practicing science, which may transcend a simple appreciation of the beauty of nature, because such appreciation is affected by previous, and often specialized, knowledge and because the practices of science are themselves sources of experiences of beauty. (b) Scientists, as any other human being, inevitably have personal feelings and emotions towards, and in response to, their work. Emotions may affect scientists' professional judgements in multiple ways, both positive and negative. (c) In particular, emotions and personal taste affect scientists' choices to pursue science in general, but also particular problems and solutions. (d) Thus, scientists "personal subjectivity" —understood as referring to their personal feelings and emotions, interests, motivation, and taste— inevitably plays a role in science. However, this does not mean that science is a subjective enterprise, in large part because science is socially validated through consensus processes among peers.

Attitudes Towards Science: Interest

Next to aesthetics, the other fundamental concept grounding the present study is that of attitudes towards science. There is wide range of constructs that fall under the blanket term "attitudes" and that are relevant in science education research. These are often closely interrelated and not unambiguously defined, and include constructs such as values, achievement emotions, self-efficacy, and interests (Tytler, 2014). However, it is broadly accepted that attitudes are closely associated to motivation and that these constructs, though belonging to the affective domain, affect students' orientation to learn and learning achievement (see e.g. Koballa and Glynn, 2013; Tytler, 2014, and references therein). A prominent example is the relationship between interest and learning.

The term interest can be defined as "a need or desire to give selective attention to something that is significant to the individual, such as an activity, goal, or research area."

(American Psychological Association, n.d.). As highlighted in Hidi and Reninger's (2006) "Four-Phase Model of Interest Development", interest can evolve from being a fleeting state triggered by the environment to becoming an enduring state associated to long term goals and persistence, but at all stages of interest development interest supports learning by enhancing cognitive processes (e.g., attention and recall) as well as persistence and effort. As this model suggests, interest, like other attitudinal and motivational constructs, is not a static personal state. Rather, it can change according to the environment and behavior of the individual. Thus, in particular, interest in science can be expected to be affected by what is done in the science classroom.

In the context of the present study having "positive attitudes towards science" will refer to having interest in science, or in learning more about science, regardless of its stage of development. Moreover, being motivated to learn more about science will be understood as a manifestation of interest in science.

Purpose of the Study

The purpose of the present study was to develop, implement, and assess the effectiveness of an intervention geared towards PSTs and based on a short story that weaves episodes from HOS with explicit statements and questions to highlight the role of aesthetics in science.

The rationale for focusing on aesthetics was twofold. In the first place, as discussed in the previous chapters, this aspect of NOS has received relatively little attention in the NOS literature, even though it is closely connected to several key aspects of NOS may thus contribute to foster a more coherent understanding of science as a human enterprise. In the second place, by humanizing science, a better understanding of the role of aesthetics may help improve PSTs' attitudes towards science. Moreover, PSTs are the ones who will eventually be in charge of the education of students in K-12 school settings and beyond, and therefore constitute an essential target group of NOS education if one hopes NOS understanding to be effectively fostered in school curricula (see e.g. McComas et al., 2020).

Accordingly, the design and assessment of the intervention were guided by the following research questions:

1. What is the effect, if any, of the intervention on PSTs' interest in science?
2. What is the effect, if any, of the intervention on PSTs' understanding of the role of aesthetics in science?

Methodology

This study examined the effects of an intervention based on a historical short story on PSTs' understanding of the role of aesthetics in science and their attitudes towards science. Assessment is primarily based on two surveys, implemented right before and after the intervention. The study used a mixed-methods approach (Johnson and Onwuegbuzie, 2004), where both qualitative and quantitative data analysis are used to address different aspects of the research questions. The participants and instructional context, the structure and design of the intervention and assessment instruments, and the data analysis process are described below.

Participants and Instructional Context

The participants in this study were 14 pre-service teachers enrolled in two sections of the course EDSC-4093: Inquiry-based Science Teaching at the University of Oklahoma. This is an undergraduate level course that introduces students to NOS and other fundamental principles of science education. Students in the course were pursuing a degree either in elementary education, early childhood education, or special education. This is the first course on science pedagogy that these students take. Students in the class were overwhelmingly female and white.

To recruit participants, I visited their classrooms a week before the intervention, read a brief script describing the study, and distributed a flier with a link to an electronic informed consent form which is reproduced, together with the consent script and flier, in Appendix A. The consent form was created and distributed using the Qualtrics on-line platform. All students in the course completed the instructional intervention as part of their regular course but those students who agreed to participate in the study agreed to complete a pre- and post-intervention survey and could also agree to be contacted for a follow-up interview, though the latter was not required. Of a total of 27 students, in both sections, 19 initially agreed to participate but only 14 completed both surveys. Four participants agreed to be contacted for a follow-up interview but only two, one from each section, were eventually available for said interview.

Structure of the Intervention

The intervention had two components, an in-class component centered around reading and discussing a short historical story and an asynchronous component that asked students to engage further with the science ideas in the story through the use of rich verbal or visual images. The story and both components of the intervention are described in detail below.

Historical Short Story

The historical short story, which I developed for the intervention, is reproduced in Appendix C. It weaves together episodes from the historical development of the concept of energy that highlight different aspects of the role of aesthetics in science, as well as connections between science and the arts relevant to this historical context.

To develop the story I used the extensive resources and professional support available at the History of Science Collections at the University of Oklahoma's Bizzell Memorial Library. Primary sources included correspondence and scientific papers by James Clerk Maxwell (Maxwell and Harman, 1990) and Michael Faraday (Faraday, 1852). Other useful sources included biographical (Campbell and Garnett, 1884) and commemorative (Thomson, 1931) accounts of Maxwell's life and work, as well as several books addressing relationships between the arts and science (particularly Clarke, 2001 and Gold, 2012), and scientists' artistic work (particularly Illingworth, 2021). Beyond specific sources cited in the story itself, these resources were essential for me to develop a personal understanding of the historical and scientific context and of the character of the scientists at the center of the story, necessary to represent them accurately.

The structure of the story is primarily informed by the NOS education research literature and follows closely the structure of historical short stories by Clough et al. (2010) and Clough (2011 & 2020). Accordingly, the story is short and centered around a topic that is relevant in the instructional context where it was to be implemented, facilitating the integration of the intervention in that context. In fact, the concept of energy plays a broad and fundamental role in modern science and, accordingly, in the standard science curriculum that these pre-service teachers will need to address in their classrooms at any grade-level, with Energy and Matter one of the seven cross-cutting concepts in the Next Generation Science Standards (National Research Council, 2013) and the Oklahoma Academic Standards for Science (Oklahoma State Department of Education, 2020).

A particularly important feature, also modeled in the stories by Clough and collaborators (Clough, 2011, 2020; Clough et al., 2010), is that the story explicitly addresses each aspect of the role of aesthetics in science through clarifying statements and questions embedded in the text. These aim at making the most relevant NOS ideas explicit and at fostering the personal reflection and discussions of these ideas by readers, two essential characteristics of effective NOS instruction (McComas et al., 2020). More specifically, the story includes four sets of clarifying statements and/or questions embedded at different points in the story. In each of these sets, statements and questions build upon each other. The statements are intended to help readers summarize the information in the story to focus on the essential ideas and the questions are intended to elicit personal reflection about the implications of these ideas. Accordingly, three of these sets address the three main aspects of the role of aesthetics in science, i.e., experiences of beauty, emotion, and taste. In particular, when addressing the issue of taste, the statement and questions relate it to the idea that scientists make choices and questions how these are affected by aesthetic considerations and the implications of this element of subjectivity for science more broadly.

Additionally, one statement and question set addresses the interplay between science and the arts that is evident in some of the episodes narrated in the story, which were in turn chosen specifically for that purpose. These highlight how both science and the arts rely on rich visual and verbal images and analogies, in the hope that highlighting connections between science and the arts would help in disrupting the common dichotomous view of these ways of knowing and draw on the universal appeal of art to improve attitudes towards science (Flannery, 1991, 1992; Girod et al., 2003; Pugh and

Girod, 2007; Root-Bernstein, 1996; Wickman, 2006; Wickman et al., 2022.

The structure of the story is also consistent with, and informed by, Pugh & Girod's (Pugh and Girod, 2007) framework to foster transformative, aesthetic experiences. Its historical nature restores the original context in which the original scientific ideas about energy were conceived, fostering understanding of their original significance. Moreover, the content itself aims at promoting interest and emotional engagement in the reader, in particular as it highlights historical examples of scientists' own emotional engagement but also through elements of the presentation of the story, such as illustrations and wording. Finally, the story addresses how rich imagery and metaphors, highlighted by Pugh and Girod as an important tool to foster understanding and appreciation of scientific ideas, were used by scientists to advance and communicate their own understanding of the concept of energy. These aspects are also explicitly emphasized through questions for reflection and discussion embedded in the text.

I used feedback from an expert in science education, an expert in the history of science, and three scientists to edit initial drafts of the story, in order to ensure that it was comprehensible and engaging, and that the embedded questions functioned as intended.

Synchronous Activity

The synchronous part of the intervention took place midway through the semester. I visited each section of the EDSC-4093 course as a guest instructor and used 80 minutes, about half, of their usual weekly class for this activity. All students present at the time took part in the activity, regardless of whether they were participants or not. A total of 24 students participated, with seven in the first section and 17 in the other. The room where students meet for this class has a set of round tables to facilitate small-group work and discussions. Students sat around these tables in groups of three to five.

The activity had three parts. In the first part, which took about 15 minutes, after introducing myself briefly I started by projecting a slide with the essential questions: (a) Do scientists' experiences of beauty, emotion, and taste play a role in how they do science?

and (b) What does this tell us about the work of scientists and scientific knowledge? Then, to elicit students ideas, I projected a photograph of a beautiful natural landscape. I described how being in that situation produced in me a deep sense of awe and asked them to consider similar experiences of their own. When asked to see the landscape through the perspective of a scientist, students contributed elements that a scientist might be interested in studying in such a situation (including light phenomena, geological features, plants, and animals). I then asked what effect such a scientific perspective might have on the more contemplative perception of beauty in the landscape that we had initially talked about. I then presented a short video of the physicist Richard P. Feynman discussing this question (FreeScienceLectures, 2007). Feynman addresses how, contrary to the belief of an artist friend of his, a scientific approach to nature added much to his experience of beauty in the natural world, without taking away from the beauty perceived in absence of a scientific perspective. After watching the video, I asked students to share arguments that might support the positions stated by Feynman and his artist friend.

In the second part, students read the historical short story, which was available on the Canvas page of the course. I asked them to discuss the question embedded in the story with their table groups and to take some notes to summarize their discussions so that they could share them later with the rest of the class. In both sections this took about 25 minutes, during which I circulated around the room listening to their discussions and contributing any necessary clarifications and observations to encourage the discussion.

In the third part, which took about 40 minutes, after all small groups had finished working through the story I led a whole class discussion where students shared some of their reflections in response to each of the questions embedded in the story and its content. I started the discussion by asking student to share their reflections about the first question in the story and then continued bringing up the remaining questions as they became relevant to the ongoing discussion, whenever possible. I also brought up additional questions that I had observed come up during the small-group discussions and which seemed important to address with the whole group. This included, in both classes, the idea of science as a communal endeavor and the consensus mechanisms of science. We finished this discussion by consolidating their contributions into an answer, and supporting arguments, to the essential question posed at the beginning of the activity, i.e., Do scientists' experiences of beauty, emotion, and taste play a role in how they do science? Finally, we had a discussion about the importance of this topic in the context of science teaching and learning, in particular, about the implications of students not having an understanding of the role of aesthetics in science. I finished the activity by providing a brief description of the asynchronous activity.

Asynchronous Activity

The asynchronous activity was delivered via Canvas to all students in the course where the intervention was implemented. The activity was assigned no grade and so completion, though encouraged, was not required as part of the course. The course instructors gave students two weeks to turn in their submissions to Canvas. All but three of the study participants submitted the assignment. The assignment, as provided to the students, is reproduced in Appendix D and summarized in what follows.

Students were presented with the following quote from physicist Richard P. Feynman (Feynman et al, 1999) as an example of a rich verbal image representing a scientific process:

> The world looks so different after learning science. For example, the trees are made of air, primarily. When they are burned, they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into trees, and in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead...These are beautiful things, and the content of science is wonderfully full of them. (p.186)

Students were then asked to create a visual or verbal representation to the concept of energy and/or the principle of energy conservation using a medium of their choice. They could use Feynman's quote as a starting point, representing that specific image in another medium, or use a different image, original or from another source. Additionally, they were asked to submit a brief artist statement, one paragraph where they described their work and to share their work though Canvas.

The assignment was informed by the idea of scaffolding an aesthetic experience from the science content, fostering a re-seeing of the content though images and metaphors and establishing wider or stronger connections between the content and the individual's other personal interests and experiences (Pugh and Girod, 2007). Its format follows closely the format of an assignment I experienced in the Models of Instruction course, ILAC-5003, with Dr. Heidi Torres, during the Spring 2020 semester.

Data Collection

To assess the effects of the intervention, according to the research questions guiding the study, two surveys were developed and distributed to all participants, a pre-intervention survey and a post-intervention survey. In what follows, I will refer to these as the pre-survey and post-survey. Post-survey responses were collected between one and three weeks after the submission deadline for the asynchronous activity. Additionally, some participants were contacted for a follow up interview. These took place between five and six weeks after the the submission deadline for the asynchronous activity. The content and development of the surveys and interview will be described in what follows.

Survey Development and Distribution

The surveys were developed and implemented using the Qualtrics software on-line platform. Both surveys are reproduced in appendices E and F. Participants took around 10 minutes to complete each survey. All except one of the participants responded to all survey questions. The one exception ignored one open-ended question in the pre-survey. Each survey has three blocks of questions, which are described in what follows and summarized in Table 1.

The first block addresses the respondent's understanding of the role of aesthetics in

Table 1

Pre- and post-survey questions.

ID	Question	Pre	Post
Block 1:			
P1*	Some people say that doing science is a completely rational and objective endeavor, where personal feelings and emotions play no role. Others argue that science is inevitably affected by the personal feelings and emotions of scientists. How do your own views compare to these two positions?	x	x
P2*	Some people say that taking a scientific perspective makes the natural world more interesting and reveals more aspects of its beauty. Others argue that from a scientific perspective the natural world looks dull and that the beauty of nature is reduced and lost when analyzed scientifically. How do your own views compare to these two positions?	x	x
P3*	Some people say that good scientific research is completely objective in that there is only one right and rational interpretation of the evidence, so that the personal taste of a good scientist is completely irrelevant to their work. Others say that the evidence gathered by scientists have multiple plausible interpretations, and that good scientists rely on their personal taste and intuition to choose between alternative interpretations of the evidence. How do your own views compare to these two positions?	x	x
Block 2:			
L1†	To what extent would say that science is personally interesting to you?	x	
L2†	To what extent would you say that you are personally motivated to learn more about science?	x	
L3†	To what extent did this intervention portray science as more interesting than you previously thought?		x

*Open-ended question. †Five point Likert scale question.

Notes: Labels in the ID column are arbitrary, their only purpose is to facilitate referencing the questions in the text. The table continues in the next page.

ID	Question	Pre	Post
Block 2:			
L4†	To what extent did this intervention affect your interest in science in general?		x
E1*	Please, briefly explain your response to [question L4].		x
L5†	To what extent did this intervention affect your interest in the concept of energy?		x
L6†	To what extent did this intervention motivate you to learn more about science?		x
L7†	To what extent did this intervention affect how often you think about the concept of energy in relation to events in your everyday life.		x
L8†	To what extent did this intervention affect your understanding of the concept of energy?		x
Block 3:			
L9	In your daily life, how often does your knowledge of scientific ideas and ways of thinking:		
.a †	Give you a valuable perspective for making sense of the world around you?	x	x
.b †	Help you figure out the best option when taking an important decision?	x	x
.c †	Foster a greater appreciation of some aspect of the world around you?	x	x
L10	Thinking broadly about the concept of art as encompassing literature, poetry, visual arts, music, performative arts, etc. In your daily life, how often does art:		
.a †	Give you a valuable perspective for making sense of the world around you?	x	x
.b †	Help you figure out the best option when taking an important decision?	x	x
.c †	Foster a greater appreciation of some aspect of the world around you?	x	x
P4 †	Some people would say that science and art have nothing in common, while others would argue that they are both human ways of knowing, more similar than they are different. What would you say?	x	x
E2*	Please, briefly explain your response to [question L4].	x	x

*Open-ended question. †Five point Likert scale question.

science. It is constituted by three open-ended questions which face the respondent with two opposing hypothetical positions, one accurate and the other inaccurate, regarding the role of one of the three aspects of aesthetics in science, a common way of eliciting NOS understanding (Abd-El-Khalick, 2014). This section is identical in the pre-and post-survey, allowing for a direct comparison of each participant's responses before and after the intervention. It was designed to assess the effects of the intervention in response to the second research question of the study. Because these question address the respondent's understanding of a complex aspect of NOS, a open-ended format seemed most appropriate as it allows for respondents to express both an overall position as well as their reasoning (Abd-El-Khalick, 2014).

The second block addresses the respondent's self-reported attitudes towards science and the intervention. In the pre-survey the questions address the respondent's personal interest and motivation to learn science. In the post-survey, the questions address the respondent's perception of the effect of the intervention on their personal interest and motivation to learn science in general, as well as their perceived understanding of the concept of energy, and their interest and motivation to learn more about it. This section contains mostly Likert scale questions but respondents are asked to give a short explanation of their answer to question L4, namely, "To what extent did this intervention portray science as more interesting than you previously thought?". The questions in this block were designed in response to the first of the research questions guiding the study. They are modeled in the self-report strategy used by Clough et al. (2010) with similar purposes.

The third block addresses the personal relevance of science and art in the respondent's every day life through a set of Likert scale questions. Additionally, the last question of the block addresses to what degree the respondent perceives art and science to have similar characteristics as human ways of knowing. This last question asks for a Likert scale answer followed by a open-ended explanation. The questions in this block are identical in the pre- and post-surveys. They were designed to assess to what degree the respondent perceives there to be a dichotomy between science and art, both before and after the intervention.

Finally, question L7 addresses the degree to which the respondent perceives that the intervention has affected how often they think about the concept of energy in their everyday lives. This question is informed by Pugh & Girod's (Pugh and Girod, 2007) framework of transformative, aesthetic experiences, according to which one characteristic of such an experience is an enhanced value and transfer of a scientific idea.

After developing the surveys, I did some pilot testing of the items among a diverse audience including one expert in education research, three scientists, and two other non-scientists to ensure that they were comprehensible and functioned as intended.

Follow-up Interviews: Protocol and Implementation

Participants who agreed to be contacted for an interview during the consent process were contacted via email once all post-survey data had been collected, during the last week of the semester. Only two participants responded affirmatively and could be interviewed. The interviews took place over Zoom and each lasted around 20 minutes. The audio of the interviews was recorded to produce a transcript for later analysis.

The purpose of the interviews was, primarily, to assess the accuracy of interpretations arising from the analysis of the participants' answers to the pre- and post-surveys, as well as to clarify any doubts regarding their answers. Additionally, the interviews provided an opportunity to ask for elaboration on the participants' asynchronous activity submission, and to ask for general feedback about all elements of the intervention. Accordingly, the interviews were semi-structured: Most questions emerged from the specific responses of each interviewee to the remaining instruments, but were presented using a pre-determined structure and order. When necessary, probing question were used get a deeper insight into the understandings suggested by their answers. Finally, questions asking for feedback were also pre-determined and left for the end of the interview. The interview protocols are reproduced in Appendix G.

Data Analysis

The analysis focused on data from the surveys' first and second blocks. Survey data from Likert scale and open-ended questions were analyzed separately. Likert scale questions in the pre- and post- survey were tallied and the results used to assess and compare students attitudes towards science, the science content of the intervention, and the intervention itself before and after its implementation. Given the small number of participants, analyses beyond descriptive statistics were not appropriate. In turn, participants' responses to the open-ended questions were categorized using an inductive qualitative analysis (Merriam and Tisdell, 2015). First, all pre- and post-survey answers to each question were grouped together and analyzed independently, as described in the Coding subsection. Pre- and post-survey responses were then compared to detect changes in each participant's NOS views.

Coding of Open-ended Questions

The qualitative content analysis of the responses to each open-ended question was performed independently. As a first step, the answers to the open-ended questions, P1, P2, and P3, which were framed as a choice between two positions, were classified according to which position was best reflected by the response. If the answer showed no clear choice between the two positions it was classified as *undecided.* The few answers that were either unclear, did not directly address the question, or were missing altogether were classified in a single category as *unclear or missing.*

After categorizing the overall position of each response, a second cycle of coding was conducted to provide a deeper analysis of the extent to which PSTs' responses to P1-P3 reflected views that are consistent with an appropriately accurate understanding of the role of aesthetics in science, as defined for the purposes of the present study in the Theoretical Framework section. This consisted of an initial open coding process of individual answers from which a set of analytical categories emerged (Merriam and Tisdell, 2015), informed by the theoretical framework of the study. The overall aim throughout this last step was to organize the answers according to the sophistication of NOS understanding they expressed, so that responses that expressed similar views would fall in the same category.

This analysis resulted in a meaningful classification scheme for the answers to question P1. Unfortunately, the same cannot be said of questions P2 and P3. In the case of question P3 the answers in the sample addressed themes that were too disconnected from each other to allow for meaningful categories to emerge, especially since a large fraction of the responses fail to address the question directly and rather reflect on diverging interpretations of what is being asked. In contrast, in the case of P2 the answers were not significantly different regarding the degree to which they accurately represent the effect of a scientific perspective on one's perception of beauty. Nevertheless, themes identified during the initial open coding process of the responses to P2 are summarized in the results section, as they offer some insight into the respondents' perception of why taking a scientific perspective makes the natural world more interesting and reveals more aspects of its beauty. Finally, in the case of responses to question P1, a successful scheme did emerge from the analytical coding process, according to which answers are classified into one of six categories indicating increasingly sophisticated characterizations of the role of personal feelings and emotions in science. The classification scheme for question P1 is summarized in the Results section and illustrated with exemplars of respondents' answers.

Coding of responses to question E2 followed a similar process as that of P1-P3, with open-coding of individual answers followed by their classification according to a set of emerging categories. In the case of E2 the overall goal was to reach a better understanding of the participants' self-reported change in their interest in science as a result of the intervention. Four themes emerged from this analysis, which are summarized and illustrated with exemplars in the Results section.

Finally, the follow-up interviews were used as a tool to asses the accuracy of my analysis. During the initial stages of the analysis, I used them to assess my interpretations of the PST's survey answers. Then, after coding and analyzing all the survey data, I used the interview responses to assess the accuracy of that analysis, by comparing the results obtained for the interviewees to the understanding they expressed in the much more detailed responses provided in their interviews. In both instances, the interviews largely confirmed my analysis, as will be addressed in detail in the Results section. There, interview quotes will be presented to illustrate themes derived from the analysis of survey data.

Results and Analysis

Attitudes Towards Science

As shown in Table 2, respondents' self-reported initial attitudes towards science were moderately positive, most reported being at least somewhat interested in science and somewhat personally motivated to learn more about science in the pre-intervention survey, while none selected the survey items indicating extreme negative or positive attitudes towards science (i.e., *not at all* and *to a very large extent* interested in/personally motivated to learn more about science). However, the post-survey data, shown in Table 3, shows that all respondents attributed to the intervention an enhancement of their attitudes towards science. In particular, all respondents self-reported that the intervention portrayed science as more interesting than they previously thought at least somewhat, while half found that it did so to a large extent. Moreover, most reported an increase in their interest in science in general as a result of the intervention, and all respondents attributed the intervention with motivating them to learn more about science, with half stating that it motivated them to do so to a very large extent.

The above mentioned results do not change significantly when it comes to respondents' post-intervention attitudes towards the concept of energy, specifically. Table 4 shows that most respondents report that the intervention somewhat increased their interest in, and understanding of, the concept of energy. While some reported that the intervention had no effect on their interest and understanding of the concept of energy, none reported a decrease of either interest nor understanding.

All the respondents reported in the post-intervention survey that the intervention increased, to some degree, how often they think about the concept of energy in their everyday lives. This may be a simple consequence of the fact that the post-intervention survey was distributed only one week after the respondents were expected to submit the asynchronous activity, that required them to represent their understanding of the concept of energy and/or the principle of energy conservation using a medium of their choice. Most

Table 2

Pre-intervention survey questions regarding respondents' initial attitudes towards science, L1 and L2, in terms of the number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, in each category.

To what extent would say that science is personally interesting to you?					
	Not at all	Little	Somewhat	To a large extent	To a very large extent
N	0	1	11	2	0
%	0.0	7.1	78.6	14.3	0.0
To what extent would you say that you are personally motivated to learn more about science?					
	Not at all	Little	Somewhat	To a large extent	To a very large extent
N	0	1	11	2	0
%	0.0	7.1	78.6	14.3	0.0

submissions are elaborate representations with clear connections to the respondents' personal lives, including an array of original poems and drawings, as well as carefully curated photographs of local environments and personal activities. The corresponding artist statements portray a wide array of different perspectives on the subject of energy and energy conservation, from the abstract definition of energy as a physical concept to environmental issues. The respondents commitment to this task, evident in the quality of their submissions and highlighted by the fact that these submissions were voluntary, conveys a high level of personal engagement with the content of the intervention, although not necessarily an enduring one.

Thus, in response to the first of the research questions guiding this study, the above mentioned results show that the intervention had an overall positive, if modest, effect on the respondents' attitudes towards science, both in terms of increased interest and

Table 3

Post-intervention survey questions regarding the effect of the intervention on PSTs' attitudes towards science, L3, L4, and L6, in terms of the number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, in each category.

To what extent did this intervention portray science as more interesting than you previously thought?					
	Not at all	Little	Somewhat	To a large extent	To a very large extent
N	0	0	4	7	3
%	0.0	0.0	28.6	50.0	21.4
To what extent did this intervention motivate you to learn more about science?					
	Not at all	Little	Somewhat	To a large extent	To a very large extent
N	0	0	7	7	0
%	0.0	0.0	50.0	50.0	0.0
To what extent did this intervention affect your interest in science in general?					
	Reduced interest greatly	Reduced interest somewhat	No effect	Increased interest somewhat	Increased interest greatly
N	0	0	1	12	1
%	0.0	0.0	7.1	85.8	7.1

motivation to learn more about science. To better understand the origin of these changes, one can look at the respondents' explanation of their answer to the question: *To what extent did this intervention portray science as more interesting than you previously thought?* Table 5 summarizes the main themes in their explanation, showing that close to a third of the respondents simply commented on how they found the intervention to be interesting (rather than the science content or science in general). Others made general statements indicating that the intervention provided them with a different perspective about science, with one respondent in particular citing how the intervention allowed them

Table 4

Post-intervention survey questions regarding the effect of the intervention on PSTs' attitudes towards the concept of energy, L5, L7, and L8, in terms of the number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, in each category.

To what extent did this intervention affect how often you think about the concept of energy in relation to events in your everyday life.					
	Not at all	Little	Somewhat	To a large extent	To a very large extent
N	0	2	9	3	0
%	0.0	14.3	64.3	21.4	0.0
To what extent did this intervention affect your interest in the concept of energy?					
	Reduced interest greatly	Reduced interest somewhat	No effect	Increased interest somewhat	Increased interest greatly
N	0	0	3	10	1
%	0.0	0.0	21.4	71.4	7.1
To what extent did this intervention affect your understanding of the concept of energy?					
	Reduced understanding greatly	Reduced understanding somewhat	No effect	Increased understanding somewhat	Increased understanding greatly
N	0	0	2	10	2
%	0.0	0.0	14.3	71.4	14.3

to think about science "in a different frame of mind that wasn't just a lab". On the other hand, some respondents attributed their increased interest in science to the fact that the intervention had the effect of humanizing scientists, as one respondent explained in the post-intervention interview,

> I feel like scientists can get rep as being very cold, isolated. Only focus on the results. This [intervention] helped to humanize [them]. Be like, no, they are just people.

Table 5

Main themes in respondents' answers to the post-intervention survey question regarding the effect of the intervention on their interest in science, E1, as well as number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, of answers in the pre- and post-intervention survey that contain each theme. Each answer is assigned a single theme.

Theme	Description	Exemplar	N	%
Engagement	Identifies the intervention as engaging and/or having an effect on the respondent's engagement with science/science content.	There was an entire thought process considered that sparked incredibly engaging and fascinating discussion, prompting thought processes that may not otherwise be considered day to day.	4	28.6
Humanizing	Identifies the effect of highlighting the human aspects of science, enhancing the respondent's perception of scientists as regular people.	I realized there is more art and opinion involved with science. I see scientists more as 'normal humans' with feelings and interests than I did before.	3	21.4
Connection to the arts	Identifies the effect of highlighting the relationship between science and the arts.	I did not think about science and art being talked about in the same capacity prior to the intervention. It helped me realize that they are, and can very much be interconnected.	2	14.3
Perspective	Identifies the intervention as broadening the respondents perspective on science.	It allowed me to think about science in a different frame of mind that wasn't just a lab.	2	14.3
No answer	No answer given in the survey	NA	3	21.4

Furthermore, a couple of the respondents stated that their interest rose because the intervention disrupted the stereotypical dichotomy between science and the arts, a central element of the historical short story that constitutes the centerpiece of the intervention.

Notice that, as addressed in the Theoretical Framework section, this theme is closely related to that of humanizing scientists, and consequently science, given that the arts are broadly considered as an inherently human activity, an expression of our creative skill and subjective nature (Oxford Languages, n.d.). Indeed, that science involves creativity, and how that understanding makes science seem more interesting, was explicitly addressed by the other interviewee, who stated

> Science to me has always been (...) concrete. This is what it is, fact. I think [the intervention] kind of made me realize that it's a little bit more deeper than that. And we can take science in a different lens than what I normally thought it could be looked at. So that's what I mean, It made it more interesting, more creative.

These responses, in what regards the human elements of science, support a positive assessment of the intervention's effectiveness, not only in what regards the respondents' interest in science but also in terms of their NOS understanding. However, a more detailed analysis of the latter is necessary and will be addressed in the next section.

Understanding of the Role of Aesthetics in Science

In the previous section I described how respondents' self-reported an enhancement of their attitudes towards science as a result of the intervention. Some respondents attributed this change to what could be summarized as an expanded understanding of the human elements of science, a fundamental goal of NOS teaching (McComas, 2020b). However, the degree to which their understanding of the role of aesthetics in science changed as a result of the intervention cannot be meaningfully assessed from the above mentioned data. Accordingly, we now turn to the analysis of the responses to questions P1, P2, and P3 of the pre- and post-surveys (see Table 1), which specifically address the respondents' understanding of the role of the elements of aesthetics in science, i.e., personal feelings and emotions, experiences of beauty, and taste and choice, respectively.

Table 6

Summary of respondents' pre- and post-intervention positions with respect to the role of the elements of aesthetics in science, in terms of the number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, in each category.

	Pre		Post	
	N	%	N	%
In response to question P1 - Personal feelings and emotions:				
Recognized role of personal feelings and emotions in science.	11	78.6	13	92.9
Did not recognize role of personal feelings and emotions in science.	2	14.3	0	0.0
Undecided about role of personal feelings and emotions.	1	7.1	1	7.1
In response to question P2 - Experiences of beauty:				
Recognized the role of science as enhancing experiences of beauty.	11	78.6	13	92.9
Undecided about the role of science on experiences of beauty.	2	14.3	1	7.1
Answer is unclear or missing.	1	7.1	0	0.0
In response to question P3 - Taste and choice:				
Recognized the role of choice in science.*	8	57.1	10	71.4
Did not recognize the role of choice and/or personal taste in science.*	1	7.1	0	0.0
Undecided about the role of personal taste and choice in science.*	0	0.0	0	0.0
Answer is unclear or missing.	5	35.7	4	28.6

* Only $N = 8$ (27%) of all answers to the pre- and post-intervention surveys combined address the role of taste and/or choice explicitly. The rest only address the idea that multiple plausible interpretations of scientific evidence are possible.

Table 6 summarizes the respondents' answers to questions P1, P2, and P3. One can see that the number of respondents that recognized the role of each element of aesthetics increased between the pre- and post-surveys. Notice that in the case of questions P1 and P2 the increase, although modest, is almost as high as possible, given that in the post-survey all but one of the respondents recognized a role for personal feelings and emotions in science and attributed to a scientific perspective an enhancement of their experiences of beauty in the world. On the other hand, both in the pre- and post-surveys a smaller number of respondents recognized a role for personal taste and choice in science in response to question P3. To better understand the reasons for this disparity it is useful to analyze the responses to each question separately and in more detail, as follows.

Role of Personal Feelings and Emotions

While Table 6 shows that the vast majority of the respondents recognized some role for personal feelings and emotions in science both before and after the intervention, a closer analysis is necessary to establish what they perceive that role to be. Accordingly, Table 7 describes six categories, emerging from the qualitative data analysis of the pre- and post-survey answers to P1, that allows for the classification of these answers according to the level of sophistication in the understanding of the role of subjectivity in science they express. On one extreme, in category S0, answers express an inaccurate understanding of science as a completely objective and rational enterprise. At the other extreme, in categories S4 and S5, answers reveal a sophisticated understanding of science as a human activity, inevitably affected by scientists' personal feelings and emotions in a complex way. However, only in category S5 do answers explicitly address the consensus mechanisms that allow for intersubjectivity to emerge from the personal subjectivity of individual scientists.

Table 7

Classification scheme for answers to question P1, corresponding to various levels of sophistication regarding understanding of subjectivity as an element of science.

Category	Description	Exemplar
S0	Expresses an inaccurate view of science as completely objective, an activity where subjectivity plays absolutely no role.	I believe that science does not have anything to do with emotions. It is a process that takes you to a solid answer.
S1	Recognizes, but cannot yet resolve, the conflict between science as completely objective and rational and science as a human endeavor. Expresses a belief that, at least under some circumstances, science must somehow remain completely objective despite human nature.	I believe the two can go hand in hand. There are personal interests that drive curiosity and exploration. Depending on the area, politics can also be involved which many people support with emotional interest. What drives the process of science might be emotion, but what results are found are hard facts and objective unless proven otherwise with new information.
S2	Recognizes that science is necessarily affected by the personal feelings and emotions of scientists as a matter of fact, without providing any further arguments or explanations. In most cases, the answer restates or closely rephrases a portion of the most accurate of the positions proposed in the question.	I think science is affected by personal feelings and emotions.

Note: Table continues in the next page.

Category	Description	Exemplar
S3	Recognizes that science is necessarily affected by the personal feelings and emotions of scientists but expresses an incomplete understanding of these effects: Emotions are represented as having either a purely motivational, and thus positive, effect or an exclusively negative effect associated to bias. Thus, the complexity of the interplay between a scientist's motivation and biases and, moreover, the way in which these contribute to, and are balanced by, the consensual processes at the heart of science are clearly not recognized.	I think people have implicit bias towards different things. And that it could play a role in the outcome of scientific studies and research. I think we can look back in history and find evidence of this. It's not right and I think science should be unbiased but people aren't and it can taint outcomes.
S4	Recognizes that science is inevitably affected by the feelings and emotions of scientists and addresses both the effects of biases and motivations, which are evaluated as negative and positive, respectively. The consensus processes of science are not explicitly recognized.	I do not think science is completely objective because science is done by people, and people are inherently bias and subjective. However, I do not think that this is always a bad thing, it is good that scientists are passionate about what they are researching.
S5	Expresses a rich understanding of the multifaceted role of subjectivity in science, including explicit reference to the consensus processes of science.	I align with the view that while the ideal of science is to be rational and objective, it is not immune to the influence of personal feelings and emotions. Scientists are human beings with biases and emotions, and these can inadvertently affect their research, from hypothesis formation to interpretation of results. However, the scientific method and peer review help mitigate these influences and promote objectivity, making science a rigorous and self-correcting process despite its human elements.

Two comments are in order with respect to this classification. First, notice that a longer answer will not necessarily be classified as more sophisticated. For example, an answer in category S2 may be very brief while an answer in category S1, while it may be elaborate, is considered less sophisticated because it includes inaccurate statements. Second, when classifying post-survey answers it was assumed that a statement made by the same respondent in the pre-survey remained valid, as long as it was not contradicted by a statement in the post-survey. As an example, consider the following pre-survey answer, classified as S3:

> I feel as though as a scientist one should (to a certain extent) be able to put their emotions and personal biases aside when collecting data and performing experiments. However, its [not] possible to completely do so. because of this there will always be a level of personal bias within science.

The same respondent provided the following post-survey answer, classified as S4:

> Personally I believe that personal feelings and science will always be linked together, simply due to the fact that we as people are intrinsically tied to our emotions. As its these emotions that give us the drive and motivations to seek out the different elements curiosity that are inherent in science.

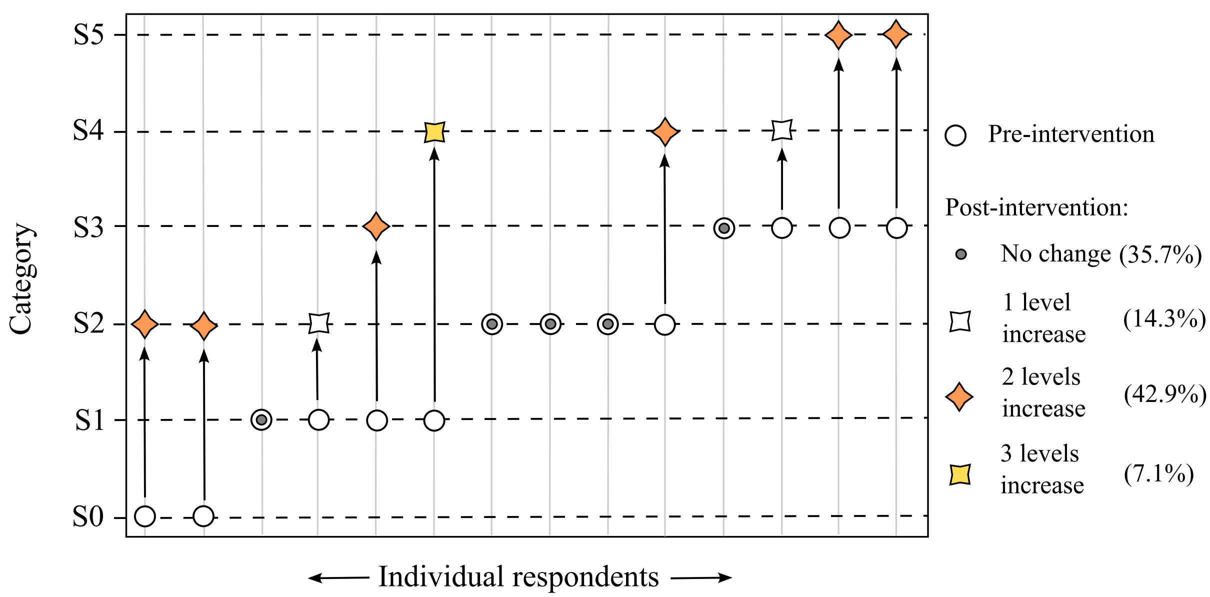
Notice that the two answers do not overlap, rather, a completely new idea is introduced in the post-survey. Read by itself, the post-survey answer should be classified as S3. However, I chose to interpret that the respondent still recognizes bias as a possible negative effect of feelings and emotions on science, as stated in the pre-survey, but has updated their understanding to include the idea of drive and motivation being inherently tied to feelings and emotion and fundamental for any human being to pursue science. Thus, according to this interpretation, the post-survey answer reveals a multifaceted understanding of the role of subjectivity in science and was classified as S4. Notice as well that it is possible, in principle, that this respondent had the understanding expressed in the post-survey answer already before the intervention and simply chose not to address it. However, the chosen interpretation, that they developed a more sophisticated understanding as a result of the intervention, was corroborated in the follow-up interview with this particular respondent.

The classification of the pre- and post-survey answers to question P1 according to the categories in Table 7 is presented in Figure 1. One can see that answers to the pre-survey where limited to categories S0-S3, showing that none of the respondents expressed an understanding of the multifaceted role of subjectivity in science, nor did they address the consensus processes of science. In contrast, one third of the post-survey answers were classified in the top two categories, S4 and S5. Moreover, for two thirds of the respondents the post-survey answer was assigned to a more sophisticated category than the pre-survey answer, with almost half of the respondents advancing by two levels in the classification.

Interestingly, Figure 1 shows that almost half of the respondents' post-survey answers fall within the S2 category. This may be explained by the fact that answers in this category require the least effort from the respondent while still expressing an accurate representation of the role of feelings and emotions in science, since answers in the S2 category do not include significant elaboration and often just restate the most accurate of the positions stated in the question itself. Accordingly, it is important to consider the possibility that answers classified within this category may underestimate the degree of understanding of a respondent at a given time, as they may have chosen not to elaborate even if they had a more sophisticated understanding. However, in terms of the pre- to post-survey change, this consideration has no effect on our overall assessment of the effectiveness of the intervention. Namely, all respondents whose post-survey answer is classified as S2 either showed no change in their pre- to post-survey answers or started at a lower category, meaning they made explicitly inaccurate statements in the pre-survey and not in the post-survey. In other words, among this sub-sample, where the presented classification suggests a positive effect of the intervention the evidence of this effect is robust.

Figure 1

Classification of pre- and post-survey answers to question P1 according to the categories in Table 7.



Note: Icons placed over the same vertical line represent a single respondent's pre- and post-survey answers, their vertical position indicates the category assigned to each answer. Icons differentiate pre- and post-survey answers and indicate by how many levels an individual's pre- and post-survey answers differ. Arrows are a visual aide connecting an individual's pre- and post- survey answers.

The risk of underestimating the degree of sophistication of a respondent's understanding from their answer is not exclusive to the S2 category but actually present for all categories between S2-S5, which exclude answers with inaccurate statements. However, in terms of the pre- to post-survey change, in all but one case the answers include statements that suggest an update in the respondent's position has actually occurred. As an example, consider the pre- and post-survey answers quoted above, where a completely new idea is introduced in the post-survey answer which, as confirmed in the follow-up interview, was developed through the intervention. Moreover, in this case the interview also revealed that the classification of the post-survey answer as S4 *underestimates* the respondent's understanding. That is, in the interview the respondent expressed how during the intervention they developed not only an understanding of motivation as an essential aspect of the role of a scientist's feelings and emotions on their work but, also, of consensus mechanisms as a way to mitigate the effect of personal subjectivity in science. More specifically, when asked about the mechanisms that address the issue of bias mentioned in their pre-survey answer, they stated:

> Definitely like peer reviews, that's probably the main thing. When you do a study and you put it out there, it's not just, oh yeah, this is a fact. People come in, they have to do their own version of that following what you have done to make sure yes, this does in fact match up. And it's not just like one person, two extra people. It's like a good chunk of extra people that are putting in the work to ensure that this is true. So I definitely think that helps to curb some of the possible pitfalls that biases can have on the scientific process.

Had the respondent reflected this understanding in their post-survey answer, it would have been classified at the highest level of understanding, S5, instead of S4.

Given the fundamental role played by consensus processes in science, it is interesting that PSTs were largely unfamiliar with this NOS idea. This is not only reflected in its absence from answers to question P1, it was evident during the synchronous activity. Given that this idea is essential to reconcile the inevitable effects of individual scientists' subjective nature and the idea of science as a rational and objective endeavour, the question naturally arose and was addressed in small- and whole-group discussions during the intervention, which resulted in one of the interviewees making the following statement:

> I think when you came to the class and we talked about all of this stuff, that's when my brain started thinking about like how to avoid bias and peer review

> was mentioned. Because originally I was just like, oh, one scientist works on one thing and then turns it in. Like in my head, it's like doing like a homework assignment. No one checks it for me, I just turn it in. But after a conversation with my table group, I was like, no. It goes through like a bunch of steps, a bunch of processes to make sure that it's done correctly before it's actually like published work.

While this is encouraging, unfortunately only three respondents expressed such enhanced understanding of this essential NOS idea after the intervention, either in the post-survey or in the interview.

Experiences of Beauty and the Role of Taste and Choice in Science

Finally, I will address the responses to question P2 and P3, regarding the relationship between science and our experiences of beauty and the role of taste and choice in science, respectively.

There was very little variation across PSTs' responses to question P2, for both the pre- and post-survey. Largely, respondents recognized the role of science as enhancing experiences of beauty. A couple of respondents were undecided or unclear in their answers, but all accepted the possibility of a scientific perspective enhancing our experiences of beauty at least in some cases. As an example, consider the following response:

> I think these two perspectives are not mutually exclusive. The impact of a scientific perspective on one's appreciation of nature can vary greatly from person to person. Some individuals find that the more they learn scientifically about nature, the more they are captivated by its beauty, intricacy, and complexity. Others may feel that certain scientific explanations detract from their personal experience of nature's beauty and wonder.

A moderate change did occur in the themes present in the responses before and after the intervention, as can be observed in Table 8. While most respondents cited a broadened outlook over *what* constitutes the natural world as the main driver of the enhancement of our perception of beauty in the pre-survey, this shifted to an enhanced understanding of natural mechanisms, or *how* things work, in the post-survey. However, the range of themes expressed in these responses remains rather limited, especially considering that other themes were mentioned by the PSTs during the intervention that are not reflected in the surveys. For example, one PST stated with great excitement that they were initially skeptical about the idea that there was beauty in science beyond the beauty inherent to the subject of study, e.g. a flower, but that after the discussion that happened in class they recognized that the process of studying the subject could be beautiful in itself.

In contrast, responses to question P3 turned out to be too different from each other to allow for a meaningful classification. This is largely due to the fact that around a third of the responses to both the pre- and post-survey are missing or do not answer the question asked. As an example, consider the following response:

> I believe science is constantly changing based on new evidence. Being able to determine a conclusion based on evidence and results is a vital factor.

This suggests that these respondents did not understand the question as intended. On the other hand, those respondents who do address the question largely focus on the issue of whether scientists have choices to make in their research but completely ignore the issue of taste. For example,

> I think that there can be multiple interpretations of evidence. That's apart of being a human being. Having different perspectives and interpretations of everything.

Table 8

Main themes in respondents' answers to question P2, as well as number (N) and percentage (%) with respect to the total number of respondents, $N_T = 14$, of answers in the pre- and post-intervention surveys that contain each theme.

	Pre		Post	
	N	%	*N*	%
Broadened outlook over what constitutes the natural world.	4	28.6	1	7.1
Exemplar: I think having a scientific perspective may make the natural world more interesting as there is so much we cannot see with our bare eyes.				
Enhanced understanding of natural mechanisms.	3	21.4	7	50.0
Exemplar: I think a science perspective can make a world beautiful. Understanding how things work in the world and why certain things do things is so beautiful in itself.				
Sense of interconnection.	1	7.1	2	14.3
Exemplar: I think that it does make science more interesting, because it shows that everything works together perfectly even if not directly seen with your eyes, and I think that is really special.				

Note: Some answers contain more than one theme and answers that just restate/rephrase the question or fail to answer it explicitly are not included in this classification.

Discussion and Conclusion

Attitudes Towards Science

The results show a positive effect of the intervention on all the respondents' attitudes towards science, evidenced by a self-reported increase in their interest in, and motivation to learn more about, science in general and the concept of energy in particular. While the effect is moderate, it is comparable to those obtained in other similar studies. For example, Clough et al. (2010) found that an intervention based on similarly structured stories implemented in an undergraduate educational context resulted in a comparable self-reported increase in students interest and their understanding of the science content of the stories. Similarly, they obtained comparable results regarding students assessment of the degree to which the intervention portrayed science as more interesting than they previously thought.

The reasons stated for this attitudinal change are also interesting, though not surprising. These can be summarized as a novel way of looking at science, acquired awareness of science as a human endeavour and scientists as normal people, and a disruption of the misconception that science and the arts have nothing in common. In fact, previous studies that have aimed at humanizing science have had similar results. For example, Hong and Lin-Siegler (2012) found that learning about scientists' struggles positively impacted students' interest in science content, as well as their academic achievement, especially for students with initially low interest in science. They concluded that the effect was related to the idea that learning about their struggles made it easier for students to relate to scientists as "normal people", when they would be otherwise perceived only through the lens of their lasting achievements. Similarly, studies that have emphasized an aesthetic understanding of science, highlighting the beauty of scientific ideas (Girod et al., 2003; Lin et al., 2011), have found improved attitudes towards science in elementary and middle-school science classrooms, and many studies have shown that arts integration improves students motivation to learn in the science classroom. Thus, learning about the role of aesthetics in science seems to humanize science and improve students' attitudes towards science in ways that are similar to this previous work.

Understanding of the Role of Aesthetics in Science

In what regards the participants' understanding of the aesthetic aspects of NOS, the results show that the study had a positive effect. Among the participants of the study, 64% exhibited a more sophisticated understanding of personal subjectivity in science as a result of the intervention. While only a few PSTs (15%) updated their position regarding the role of experiences of beauty and personal subjectivity in science, most already recognized it in the pre-survey, so that over 90% recognized these aspects of NOS after the intervention. On the other hand, the idea that personal taste may play a role in scientists' decisions proved harder to adopt, even among PSTs that already recognized other elements of subjectivity in science, in particular that evidence is subject to scientists' interpretations and choices.

It is noteworthy that the intervention presented here was significantly shorter than most interventions reported in the research literature, as evidenced in recent reviews by Cofre et al. (2019) and Khishfe (2023). Khisfe (2023), Tao (2003), and Leach (2003) have suggested that ample time is necessary to allow for enhanced understanding of NOS in interventions based on HOS. However, recently other studies based HOS have also found positive results with relatively short interventions (Aragón-Méndez et al., 2019; Cobo et al., 2022; Valencia Narbona et al., 2023). In particular, the positive results presented here may be explained by its relatively narrow focus on aesthetics in NOS and its emphasis on providing opportunities for explicit reflection and discussions of NOS ideas, qualities that are known to be crucial for effective NOS instruction (McComas, 2020b) and are accordingly targeted in the format of the story (Clough, 2020; Clough et al., 2010) that was the basis of the intervention.

Arguably, the most interesting result of the present study is the differential response to the three elements of aesthetics. That some NOS aspects seem more accessible and likely to change than others is not surprising, as highlighted in a review of empirical research by

Cofre et al. (2019). Cofre et al. found that, among studies targeting PSTs, understanding of the empirical and creative aspects of science were often among the most understood and most likely to improve, while understanding of the socio-cultural aspects and tentativeness of science were among the least understood and most difficult to change. In this study, the element that was best understood by the PSTs was that related to beauty. The idea that a scientific perspective enhances one's experiences of beauty, and thus that of scientists, was clearly articulated by the PSTs already before the intervention. This is not surprising when considering that several of their answers reference the beauty of nature, which is easily accessible to many of us in our everyday lives, and how science makes it possible for us to access more of the natural world. Interestingly, few PSTs highlighted increased *understanding* of nature as a way in which science enhances experiences of beauty before the intervention, but many more did so after it. This is in line with Flannery's (1992, p.3) assertion that an understanding of nature is where the "inner beauty" of science lies, one that comes through analysis as opposed to the evident beauty of nature itself and one that is largely misunderstood by non-scientists (Feynman and Leighton, 2001; Flannery, 1991, 1992; McLeish, 2019; Wickman, 2006). On one hand, the reported change shows the potential for targeted interventions such as the present one to reveal some of this inner beauty to students. On the other hand, given that this particular idea was the focus of much of the synchronous activity, one could have expected to find more depth of understanding in the PSTs responses after the intervention.

What is more surprising is how those experiences of beauty, were not as readily recognized before the intervention as sources of scientists' personal feelings and emotions towards their work, as some PSTs denied the role of emotions in science completely and others reduced it to scientists' conscious or unconscious biases in the pre-survey (even when they recognized a scientific perspective as enhancing our experiences of beauty in the natural world). But while understanding of the role of personal feelings and emotions in science improved after the intervention, the same cannot be said of the role of taste as a factor in scientists choices when faced with multiple plausible interpretations of data. Moreover, most PSTs completely ignored the issue of taste when asked about this situation, and focused only on whether multiple interpretations of evidence were in fact possible. Surprisingly, this was the case even for PSTs who already in the pre-survey recognized the inevitable existence of multiple interpretations of evidence and, accordingly, the need for scientists to chose among these interpretations, and despite the fact that the role of taste was explicitly addressed in the historical short story read by the PSTs during the synchronous activity and in the discussion that followed.

These apparent contradictions can be interpreted as further evidence that the role of personal subjectivity in science is not widely understood (Flannery, 1991, 1992; Girod et al., 2003; McComas, 2020b; McLeish, 2019; Wickman, 2006). They are also reminiscent of the compartmentalization of acquired NOS understanding observed by Abd-El-Khalick (2005) during a philosophy of science course, which dissipated as the course progressed and the participating PST's understanding of NOS became deeper. As such, one can speculate that the idea that scientists have biases that may translate into their work may have been easily accessible to many participants before the intervention due, for example, to the common presence of this notion in popular media and current social narratives (Ophir and Jamieson, 2021), while scientists' emotions towards their work are rarely addressed publicly (Flannery, 1991, 1992; McLeish, 2019; Wickman, 2006) and are therefore harder to recognize. That is, until the intervention, where they were explicitly addressed in the context of real historical episodes.

Similarly, I will speculate that the fact that the role of taste remained largely inaccessible to the participants in this study is related to the fact that to accurately appreciate the role of taste in theory-choice requires a comfortable understanding of multiple aspects of NOS, all of which are interrelated (Osborne et al., 2003; Ozgelen et al., 2013). Among these are the theory-ladenness of observations, the idea that scientific knowledge is based on *interpretations* of empirical evidence that are also theory-ladden, and that, consequently, scientific knowledge is tentative. These aspects are among the least understood and, especially tentativeness, among the most difficult to learn (Cofré et al., 2019). But they seem hard to ignore when considering the role of scientists' personal subjectivity and, especially of their personal taste, in their work. As has been argued about the tentativeness (Mesci and Schwartz, 2017; Osborne et al., 2001, 2003) and socio-cultural embeddedness (Mesci and Schwartz, 2017) of science, the aesthetic aspects of NOS highlight a level of ambiguity in scientific knowledge that is hard to reconcile with the rational and durable nature of scientific knowledge, which is more familiar to teachers and students (e.g. Cofré et al., 2019; McComas, 2020b). Moreover, to develop a robust understanding of all these aspects of NOS requires a grasp of the fundamental notion that scientific knowledge is socially validated. However, several of the PSTs in the present study were not familiar with this notion and only three addressed it in their responses as part of coherent accounts of the role of aesthetics in science.

Limitations

The most evident limitation of the present study is the small number of participants, which limits the robustness of the results and the degree to which they can be generalized to other contexts without further study. Additionally, the fact that survey responses were rather short limits the degree to which the PSTs' understanding of the role of aesthetics in science can be accurately inferred from them. However, the interviews were very reassuring in this sense, even if their number was very limited and a larger number of interviews would have made the results more reliable.

Another notable limitation is that the stability of the positive effect observed on PSTs' understanding of the role of aesthetics in science remains unclear, given the short time span of the present investigation. While some studies have found progress in NOS understanding made during an intervention can be lost after a few months (e.g. Akerson et al., 2006), Cobo et al. (2022) recently found the positive effect of a short intervention based on HOS to be stable in a five-months delayed post-test. In the present study the post-survey was completed only one to three weeks after the end of the intervention (and three to four weeks after the synchronous activity where the short story was read and discussed). While during the interviews the PSTs showed the ability to clearly articulate the acquired understanding, these happened only five to six weeks after the intervention and they involved only two out of the 14 participants.

Finally, it should be considered that this study focused on analyzing the effect of the intervention in isolation from the methods course where it was implemented, even if said course addressed other elements of NOS. Given that the results suggest the importance of addressing the interconnections between multiple NOS aspects, taking into account the effect of the wider instructional context might have proved useful to better design and assess the intervention.

Implications and Conclusion

The results of the present study add evidence in support of the idea that using historical short stories while explicitly addressing and fostering reflection about NOS ideas is an effective way to enhance PST's NOS understanding (Aragón-Méndez et al., 2019; Cobo et al., 2022) Clough, 2020; Clough et al., 2010) and attitudes towards science. Moreover, as highlighted by Clough et al. (2011, 2010) and Clough (2020), the format of the short story used in the intervention presented here, with embedded statements and questions that explicitly address NOS ideas and foster reflection, can be easily introduced in established courses with positive results.

The results suggest that improving PSTs understanding of aesthetics in NOS is easier for some elements of aesthetics than for others, similar to what has been found with other aspects of NOS (Cofré et al., 2019; Mesci and Schwartz, 2017; Valencia Narbona et al., 2023). More specifically, minimal intervention was required for PSTs to recognize that scientists are likely to have a range of experiences of beauty while practicing science, and little more to understand that these experiences may elicit emotional reactions and personal feelings, helping humanize scientists and dispelling the misconception that science is completely objective. On the other hand, understanding the role of personal taste seems to require a more targeted intervention, one that, arguably, would foster a robust understanding of science as a human enterprise by explicitly addressing not only the personal subjectivity of scientists but also the interconnections between this and other aspects of NOS, particularly the fact that scientific knowledge is socially constructed and validated. This conclusion is suggestive of the learning progressions that have been considered for other aspects of NOS (e.g. Allchin, 2012). However, further research would be needed to explore these ideas in detail.

Other important questions remain that would require further investigation. In particular, it would be interesting to address the stability of these results by performing this study with a larger number of participants and a larger percentage of interviews to analyze the reliability of the analysis. It would also be interesting to address whether the positive effects of the intervention are durable.

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Appendix A

Recruitment script and flier

Recruitment Script (read by Claudia Colonnello Olivares)

My name is Claudia Colonnello Olivares and I am a Master's student in the Science Education program. The topic of my thesis project is how to foster understanding of the role of aesthetics in science and how that understanding affects students' interest in science.

As part of that project I have designed an instructional activity that I will implement in this course in a few weeks. I also want to assess the effectiveness of this activity. Therefore, today I want to ask you to consider participating in a research study that I will conduct on that instructional activity. Participating in this study will only mean that you will agree to be sent two electronic surveys by email and, optionally, agree to be contacted for a follow-up interview via zoom.

If you choose to participate, you will get one survey before and one after the instructional activity. Each survey will take you between 10 and 15 minutes to complete. You will not need to do any additional work in the course and none of your course work will be used for the study. If you choose to participate in the interview, I will contact you by email to agree on a good time for you and we will meet over Zoom for about 15-20 minutes. The interview will be recorded to generate a transcript to use in the study.

As soon as I start the analysis, the names of those who participate will be replaced by a number, and any other identifying information will be erased. The only way to link a student’s name to their number will be a password-protected file kept on my computer. So, if you participate, I’ll make sure your responses cannot be linked back to you.

If you don’t want to participate, your choice will not have any impact on your experience or grade in this course. I am the lead investigator of this study, and your instructor will not know whether or not you have chosen to participate.

I will now distribute a flier with a link to a form that describes the research study. Please take a moment to go to that form. After you’ve read it carefully, please use the form to indicate whether or not you want to participate. If you have any questions about the study, you can contact me using the contact information in the form.

I invite you to participate in my research project:

"Teaching about the role of aesthetics in science through a short story based on the history of the concept of energy".

This project investigates the effectiveness of an instructional activity designed to foster understanding of the role of aesthetics in science and how that understanding affects students' interest in science. The instructional activity is based on a short story that follows a series of episodes in the historical development of the concept of energy.

Please use the following QR code to access the consent form:

https://bit.ly/41Xqt49

Appendix B

Consent form

Default Question Block

Would you like to be involved in research at the University of Oklahoma?

I am Claudia Colonnello Olivares, a graduate student in the department of Instructional Leadership and Academic Curriculum. I invite you to participate in a research project entitled: “Teaching about the role of aesthetics in science through a short story based on the history of the concept of energy”. This research is being conducted in EDSC 4093: Inquiry Based Science Learning, and you were selected as a possible participant because you are a student in that course. You must be at least 18 years of age to participate in this study.

Please read this document and contact me to ask any questions that you may have BEFORE agreeing to take part in my research.

What is the purpose of this research? The purpose of this research is to examine the impact of an instructional activity that you will experience as part of EDSC 4093. The research examines how the activity impacts students' interest and understanding of the role of aesthetics in science.

What will I be asked to do? If you agree to participate, you will be asked to complete two online surveys, one before the instructional activity and one after. The instructional activity will be a part EDSC 4093, you will not be required to do any additional assignments for course, and none of your course work will be used for this study.

You will also be asked to choose whether you agree to be contacted for an optional follow-up interview at the end of the semester. You may participate in the study even if you choose not to participate in the follow-up interview, and you may opt out of participating at any point during the study.

What are the risks and/or benefits if I participate? You will be asked to complete this online consent form and two online surveys as part of the research. The organization hosting the data collection platform has its own privacy and security policies for keeping your information confidential. There is a risk that the external organization, which is not part of the research team, may gain access to or retain your data or your IP address which could be used to re-identify you. No assurance can be made about their use of the data you provide for purposes other than this research.

Audio Recordings: If you choose to participate in an interview, I will ask to audio record those conversations. There is a risk of accidental data release of those audio recordings. If this occurred, your identity and statements you made would become known to people who are not the researcher. To minimize this risk, the researcher will transfer data to, and store your data on, secure platforms approved by the University's Information Technology Office.

There are no direct benefits to you for participating.

Who will see my information? In research reports, there will be no information that will make it possible to identify you. Research records will be stored securely and only approved researchers and the OU Institutional Review Board will have access to the records.

Do I have to participate? No. If you do not participate, you will not be penalized or lose benefits or services unrelated to the research. Your experience in EDSC 4093 will not be affected and your instructor will not know whether or not you have chosen to participate.

If you decide to participate, you don't have to answer any question and can stop participating at any time.

Will my records be accessed? None of your confidential records will be used as data for this research.

Will my identity be anonymous or confidential? Your name will not be retained or linked with your responses unless you agree to be identified. Neither your name nor any identifying information will be shared with anyone other than the research team. No identifying information will appear in any published research reports.

Please check all of the options you agree to

	Yes	No
I agree for data records to include my identifiable information	○	○

	Yes	No
I agree to be quoted directly, without the use of my name	○	○

What will happen to my data in the future? Data that we use for the study will have all identifying information removed. We may retain de-identified data for future research, but any identifiable information that we collect during this study will be destroyed once the study concludes. We might share your de-identified data with other researchers or use it in future research without obtaining additional consent from you.

Who do I contact with questions, concerns or complaints? If you have questions, concerns or complaints about the research please contact the researcher:

Claudia Colonnello Olivares ccolonnello.k@ou.edu 405-881-7976

You can also contact the University of Oklahoma – Norman Campus Institutional Review Board (OU-NC IRB) at 405-325-8110 or irb@ou.edu if you have questions about your rights as a research participant, concerns, or complaints about the research and wish to talk to someone other than the researcher(s) or if you cannot reach the researcher(s).

Please print this document for your records. By providing information to the researcher(s), I am agreeing to participate in this research.

Please indicate your willingness to participate in this research study:

I agree to participate and I agree to be contacted for a follow-up interview

I agree to participate but I do not want to be contacted for a follow-up interview

I do not want to participate

To sign this document and confirm your participation in the study, please type your first and last name below:

Please provide a contact email

This research has been approved by the University of Oklahoma, Norman Campus IRB.
IRB Number:
Approval Date:

Appendix C

Historical short-story

A Story of Energy, Poetry, and Unification

Figure 1 A steam locomotive in J. M. W. Turner's *Rain, Steam, and Speed - The Great Western Railway* (1844). Steam engines were pivotal in the Industrial Revolution, during which the emerging concept of energy had great resonance within scientific circles and far beyond, in the imaginations of broad sectors of society[iv].

James Clerk Maxwell (1831-1879) was a Scottish physicist and one the most influential scientists of all times. Besides science, Maxwell also loved poetry: he wrote verses from a young age and oftentimes quoted poems in his correspondence with other scientists[i & ii]. In 1876 he wrote the poem *Report on Tait's Lecture on Force*[iii]. The lecture that inspired this poem was delivered by Scottish mathematician Peter Guthrie Tait (1831-1901) and didn't actually focus on the concept of *force*, as the title of the poem suggests. Rather, the lecture summarized the current knowledge about what was, at that time, the **developing** concept of *energy* and its relationship with the concept of force. For Maxwell, the new concept of energy seemed very superior to the old ideas about force. Moreover, the debate about the nature of energy that was taking place at the time produced a **strong emotional reaction** in Maxwell, strong enough to move him to write a poem about it! The following verses are part of his poem, notice the emotive language he used:

(...)
But see! Tait writes in lucid symbols clear
One small equation;
And Force becomes of Energy a mere
Space-variation.

Force, then, is Force, but mark you! not a thing,
Only a Vector;
Thy barbed arrows now have lost their sting,
Impotent spectre!
Thy reign, O Force! is over. Now no more
Heed we thine action;
Repulsion leaves us where we were before,
So does attraction. (...)

To understand Maxwell's reaction we must keep in mind that energy is a very abstract idea. Some scientists argue that it is nothing but a mathematical device, with no physical reality whatsoever, others argue that we simply don't yet know *what* it is. But there is agreement on the following: for every known system in nature we can compute this quantity called energy, with the amazing and useful property that doesn't change, it is *conserved,* no matter how much the system itself changes the quantity stays the same. Now, something so abstract can be very **hard to imagine**, especially if one happens to be one of the people who first develops such an idea. And so, for the pioneers of energy **language provided essential mental images to represent and make sense of the results of their various investigations**[iv]**.** These researchers were very interested in mechanical systems such as steam engines, where *movement* is key (see figure 1). To describe *movement* it was natural to use the concept of *force*, which can be defined as *that which changes the velocity of a physical object* and had been around for centuries. And so, the word *force* ended up being used to refer to various ideas related to what would later be known as *energy*, muddling the distinction between these two concepts.

This ambiguity fueled Maxwell's playful mockery of the word *force* in his poem, which he berated as an "*impotent spectre*", *"not a thing, only a vector*". Moreover, in his poem Maxwell hails his friend Tait as a kind of hero for writing "*one small equation*" making force become "*of Energy a mere Space-variation*". What Maxwell was referring to in this verse is the mathematical relationship that exists between what we now know as potential energy and force, which Tait presented in his lecture. What is interesting is that, mathematically, physical systems (like moving objects) can be described **with equivalent results** using either one of two **different formulations**: one based on forces or one based on energy. **Both descriptions yield accurate results,** but the energy formulation is often simpler to work with and many scientists find it more **elegant**. With his poem Maxwell expressed his clear **preference** for the novel energy formulation: "*Thy reign, O Force! is over*".

> *Question 1. Some people would say that good scientists see their work from a completely rational and objective perspective, where emotions don't play any role.* ***How does Maxwell's poem suggest that the opposite can be true? What does that tell you about how it feels like to do science?***

Maxwell not only wrote poems about energy, he also contributed a great deal to our understanding of it. Like many of his contemporaries, Maxwell became interested in electromagnetic phenomena, particularly in the experimental findings of Michael Faraday (1791-1867). Faraday was a remarkable experimentalist who had been studying electromagnetic phenomena for about 30 years. He found that when iron filings where placed around a magnet they arranged themselves to form intricate patterns of lines (see figure 2). To understand this phenomenon, Faraday **imagined** that "lines of force" existed in the space surrounding a magnet. He suggested these lines were a physical entity that exerted forces on the iron filings, creating the patterns he observed [v]. But the idea that force could be applied at a distance, i.e., without direct contact between two objects, remained controversial at the time. After all, even to us today, playing with a magnet can seem magical. At the time, what most scientists agreed on was that forces could only be transmitted through contact between physical objects. Of course, in that sense, gravity had long posed a notorious problem: Newton created equations to calculate gravitational forces, but provided no explanation for how gravity was transmitted through space.

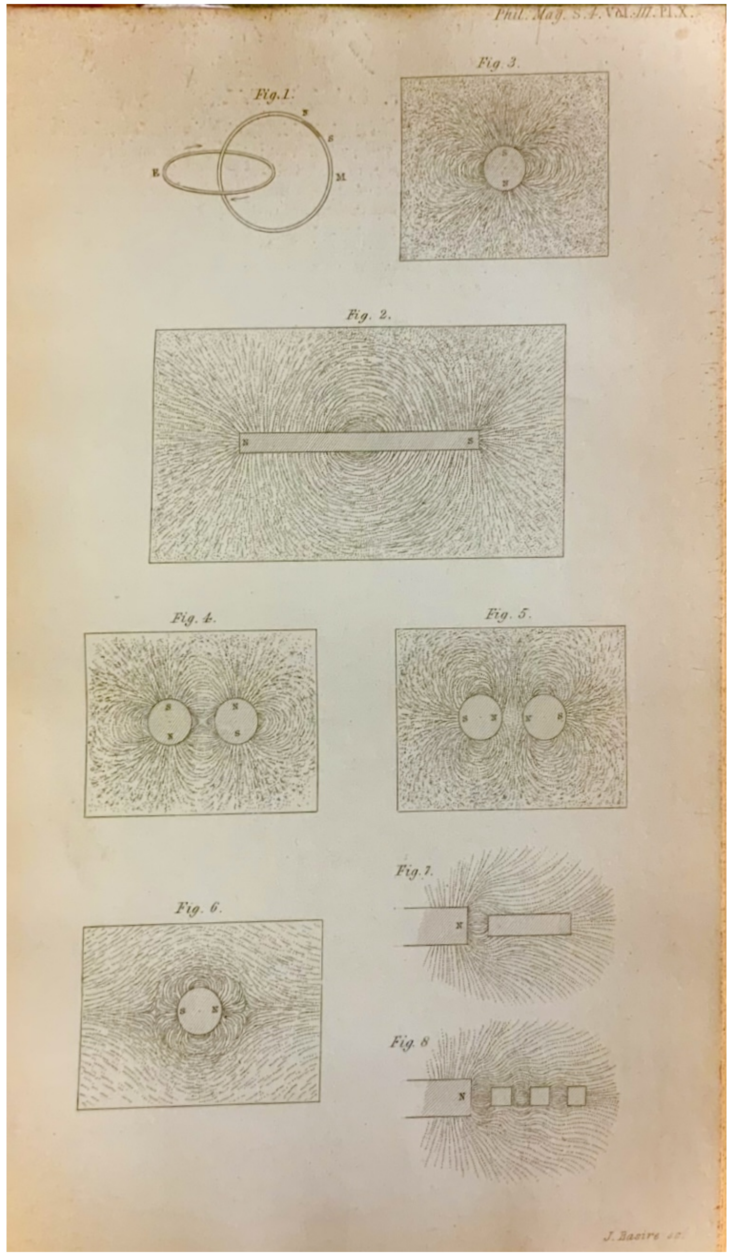

Figure 2 Drawings of Faraday's *lines of force* in a paper published in Drawings of Faraday's *lines of force* from a paper published in The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science in 1852[v].

What we would say today is that magnets are the source of an *electromagnetic field,* **a physical quantity that contains energy and extends through space, interacting with matter**, just like the Earth's *gravitational field* extends through the space around it pulling us towards the ground. But at the time of Faraday and Maxwell this idea was just emerging. In fact, it was Maxwell who would develop the mathematical description of electromagnetic fields, **and another poem would play a role in this process!**

In 1857 Faraday asked Maxwell for his opinion about the physical reality of his “lines of force”. Maxwell agreed with Faraday's ideas, envisioning what would become the electromagnetic and gravitational energy fields surrounding charged and massive bodies, respectively. He wrote in a letter to Faraday: “then your lines of force can *'**weave a web across the sky**'*”[vi], slightly misquoting a line from Alfred, Lord Tennyson's poem *In Memoriam A. H. H.*[vii]:

O Sorrow, cruel fellowship,
O Priestess in the vaults of Death,
O sweet and bitter in a breath,
What whispers from thy lying lip?

\`The stars,' she whispers, \`blindly run;
A web is wov'n across the sky;
From out waste places comes a cry,
And murmurs from the dying sun :(...)

In his letter, Maxwell added the illustration in figure 3, depicting the “lines of force” of the Sun and a planet in its orbit, which would “lead the stars in their courses without any necessarily immediate connection with the objects of their attraction”[vi].

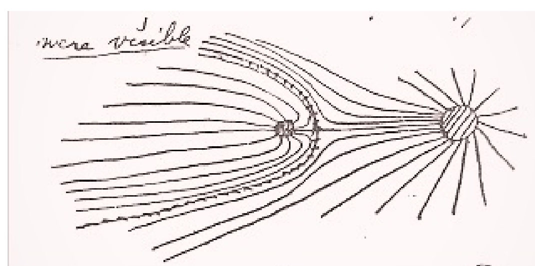

Figure 3 Drawing of the *lines of force* of the Sun and the Earth as envisioned by Maxwell in a letter to Faraday in 1857[vi].

We cannot know if the image of a “*web wov'n across the sky*” helped Maxwell **envision** energy fields, but he clearly thought the image was helpful in order to **communicate** his vision to Faraday. On the other hand, Tennyson, the author of the poem, also happened to be interested in science and often included references to scientific ideas in his work. *In Memoriam* is a meditation on mortality and refers to scientific ideas about the birth and death of our solar system: its formation, like a “*web wov'n*” from a cloud of gas across interstellar space, and its end, a “*dying sun*”[viii].

Question 2. In the story of Maxwell and Tennyson you can see a kind of reciprocity between science and the arts: one uses the other to further their goals, and both often rely on visual and verbal metaphors and analogies. ***Why do you think that is?***

The concept of energy became one of the foundations of modern physics. It underlies our understanding of all the fundamental interactions observed in nature today: it is a **unifying framework that allows us to describe phenomena that seem initially very different**, from those that occur at the very small scales of subatomic particles to phenomena occurring at the largest astronomical scales our instruments allow us to probe. It may be hard to agree on *what* precisely energy is, but **it is certainly a powerful idea**. How did we get there? That is a long and intricate story with many more contributors than we can name here. In short, by the end of the 19th century not only gravity and electromagnetism, but also light and heat could be described using the concept of energy, and the principle of conservation of energy had been established. Then, early in the 20th century, Albert Einstein (1879-1955) developed the Theory of Relativity and brought the very essence of matter, *mass*, under the framework of energy as well.

Einstein's famous equation, $E=mc^2$, states that the mass (m) and energy (E) of an object are *equivalent* and, as such, one can be transformed into the other. Until Einstein put forth his theory, mass was assumed to be a fundamental quality of matter and it was assumed to be conserved, unchanging, like energy is understood to be conserved. However, we now know that mass can be transformed into energy, effectively disappearing from a system. Also, energy can give rise to mass in empty space. These transformations occur in nuclear reactions, such as those that fuel our Sun.

The unifying power of Einstein's Theory was cited by Nobel Laureate Subrahmanyan Chandrasekhar (1910-1995) as one reason why "it is probably the most ***beautiful*** of all existing theories"[ix]. As another reason he cited its ***simplicity***. What did he mean? In the words of Einstein himself, "**if nature lead us to mathematical forms of great *simplicity and beauty* (...) we cannot help thinking that they are *true*, that they reveal a genuine feature of nature**".

> *Question 3. Scientists see beauty not only in the natural phenomena they study, but also in the ideas and mathematical models they use to represent them:* ***How may that affect their choice to*** **do** ***science? And how may it affect their decisions when facing a choice between different formulations that seem equally useful to describe natural phenomena,*** such as Maxwell's choice between a description in terms force or energy*? This seems rather subjective.* ***Is it a problem?***
>
> *Question 4. When Einstein and Chandrasekhar refer to the* beauty of a science idea*,* ***how is that similar and different*** *from the* beauty *that we see in a piece of art or a scene of nature?*

i Campbell, L (1882). *The Life of James Clerk Maxwell.* Macmillan.
ii Maxwell, J., & Harman, P. M. (1990). *The scientific letters and papers of James Clerk Maxwell* / edited by P.M. Harman. Cambridge University Press.
iii Available at: https://cudl.lib.cam.ac.uk/view/PH-CAVENDISH-P-00093/2
iv See e.g. Clarke, B. (2001). *Energy forms: Allegory and science in the era of classical thermodynamics.* University of Michigan Press.
v Faraday, M. (1852). LVIII. *On the physical character of the lines of magnetic force*. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 3(20), 401-428.
vi See i. Letter accessible at: https://epsilon.ac.uk/view/faraday/letters/Faraday3354
vii The whole poem can be found in https://rpo.library.utoronto.ca/content/memoriam-h-h-obiit-mdcccxxxiii-all-133-poems
viii Gold, B. J. (2012). *ThermoPoetics: Energy in Victorian Literature and Science*. MIT Press.
ix In Chandrasekhar, S. (1984). The general theory of relativity: Why “It is probably the most beautiful of all existing theories”. *Journal of Astrophysics and Astronomy*, *5*, 3-11.

Appendix D

Asynchronous activity

A Story of Energy, Poetry, and Unification:
Asynchronous activity

*This activity should be completed after reading and discussing the **"A Story of Energy, Poetry, and Unification"** document in class.*

To complete the activity, follow the steps below:

1. Read carefully the following statement:

   The world looks so different after learning science. For example, the trees are made of air, primarily. When they are burned, they go back to air. And in the flaming, heat is released. The flaming heat of the sun, which was bound in to convert the air into trees. And in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead...These are beautiful things, and the content of science is wonderfully full of them.[1]

   Richard P. Feynman
   Winner of the Nobel Prize in Physics, 1965

   If you want, you can watch a short video of Feynman discussing this and other related ideas here: https://youtu.be/ITpDrdtGAmo

   Notice how Feynman paints a **rich image** with his words, while using fundamental scientific ideas about energy and matter. Plants use the energy of the Sun to grow, so some of that energy remains stored in plant tissue, which can later be extracted through processes like burning.

2. Your task is to **create a visual or verbal representation** that **illustrates** the concept of energy and/or the principle of energy conservation. Note that the task is **not** to give a formal "scientific" definition of these concepts. Rather, the idea is for you construct something that **conveys a rich image** representing the concepts, much as Feynman's quote creates a verbal image: *trees as air bound with the energy of the Sun, and the light and warmth of a burning log as Sun's light and warmth being released.*

   Here are some guidelines for this task:

   - Use **any medium of your choice** to create your representation, including (but **not** limited to) photography, poetry, storytelling, drawing, sculpture, performance, fiber arts, etc.
     - You might start from Feynman's quote and create a visual representation of that image.
     - Or start from a verbal or visual image taken from another source of your choice.

1 Adapted from Feynman R. P. (1998). The meaning of it all : thoughts of a citizen scientist. Addison-Wesley.

    - Or create your own verbal/visual representation of energy that expresses your thinking.
- You will have to find a way to share what you have created using a document format suitable for a Canvas submission (.pdf, .mp4., .jpg, etc).
- **Accompany your work with a one paragraph “artist statement”,** where you describe your representation, provide a reference (if applicable) to its source, and describe briefly how your representation illustrates your understanding of the concept of energy/principle of energy conservation.

Appendix E

Pre-intervention survey

Default Question Block

Please fill in your name.

Block 1

Read carefully and answer the following questions. Keep in mind there are no right or wrong answers, we want to know about your personal thoughts regarding the issues in question.

Some people say that doing science is a completely rational and objective endeavor, where personal feelings and emotions play no role. Others argue that science is inevitably affected by the personal feelings and emotions of scientists.

How do your own views compare to these two positions?

Some people say that taking a scientific perspective makes the natural world more interesting and reveals more aspects of its beauty. Others argue that from a scientific perspective the natural world looks dull and that the beauty of nature is reduced and lost when analyzed scientifically.

How do your own views compare to these two positions?

Some people say that good scientific research is completely objective in that there is only one right and rational interpretation of the evidence, so that the personal taste of a good scientist is completely irrelevant to their work. Others say that the evidence gathered by scientists have multiple plausible interpretations, and that good scientists rely on their personal taste and intuition to choose between alternative interpretations of the evidence.

How do your own views compare to these two positions?

To what extent would say that science is personally interesting to you?

Not at all
Little
Somewhat
To a large extent
To a very large extent

To what extent would you say that you are personally motivated to learn more about science?

Not at all
Little
Somewhat
To a large extent
To a very large extent

In your daily life, how often does your knowledge of scientific ideas and ways of thinking:

	Never	Rarely	Sometimes	Often	Very often
Give you a valuable perspective for making sense of the world around you?	○	○	○	○	○
Help you figure out the best option when taking an important decision?	○	○	○	○	○
Foster a greater appreciation of some aspect of the world around you?	○	○	○	○	○

Thinking broadly about the concept of art as encompassing literature, poetry, visual arts, music, performative arts, etc. In your daily life, how often does art:

	Never	Rarely	Sometimes	Often	Very often
Give you a valuable perspective for making sense of the world around you?	○	○	○	○	○
Help you figure out the best option when taking an important decision?	○	○	○	○	○
Foster a greater appreciation of some aspect of the world around you?	○	○	○	○	○

Some people would say that science and art have nothing in common, while others would argue that they are both human ways of knowing, more similar than they are different.

What would you say?

They have nothing in common.

They have very few things in common.

They have some things in common.

They have a great deal in common.

They are essentially the same.

Please, briefly explain your response to the last question.

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Appendix F

Post-intervention survey

Default Question Block

Please fill in your name.

Block 1

Read carefully and answer the following questions. Keep in mind there are no right or wrong answers, we want to know about your personal thoughts regarding the issues in question.

Some people say that doing science is a completely rational and objective endeavor, where personal feelings and emotions play no role. Others argue that science is inevitably affected by the personal feelings and emotions of scientists.

How do your own views compare to these two positions?

Some people say that taking a scientific perspective makes the natural world more interesting and reveals more aspects of its beauty. Others argue that from a scientific perspective the natural world looks dull and that the beauty of nature is reduced and lost when analyzed scientifically.

How do your own views compare to these two positions?

Some people say that good scientific research is completely objective in that there is only one right and rational interpretation of the evidence, so that the personal taste of a good scientist is completely irrelevant to their work. Others say that the evidence gathered by scientists have multiple plausible interpretations, and that good scientists rely on their personal taste and intuition to choose between alternative interpretations of the evidence.

How do your own views compare to these two positions?

The next questions are about the story we read in class, the in-class discussions about the story, and the homework that you submitted after the class.

All of those pieces together will be referred to as "the intervention."

To what extent did this intervention portray science as more interesting than you previously thought?

Not at all
Little
Somewhat
To a large extent
To a very large extent

Please, briefly explain your response to the last question.

To what extent did this intervention affect your interest in science in general?

Reduced interest greatly
Reduced interest somewhat
No effect
Increased interest somewhat
Increased interest greatly

To what extent did this intervention affect your interest in the concept of energy?

Reduced interest greatly
Reduced interest somewhat
No effect
Increased interest somewhat
Increased interest greatly

To what extent did this intervention motivate you to learn more about science?

Not at all
Little
Somewhat
To a large extent
To a very large extent

To what extent did this intervention affect how often you think about the concept of energy in relation to events in your everyday life.

Not at all
Little
Somewhat
To a large extent
To a very large extent

To what extent did this intervention affect your understanding of the concept of energy?

Reduced understanding greatly

Reduced understanding somewhat

No effect

Increased understanding somewhat

Increased understanding greatly

In your daily life, how often does your knowledge of scientific ideas and ways of thinking:

	Never	Rarely	Sometimes	Often	Very often
Give you a valuable perspective for making sense of the world around you?	○	○	○	○	○
Help you figure out the best option when taking an important decision?	○	○	○	○	○
Foster a greater appreciation of some aspect of the world around you?	○	○	○	○	○

Thinking broadly about the concept of art as encompassing literature, poetry, visual arts, music, performative arts, etc. In your daily life, how often does art:

	Never	Rarely	Sometimes	Often	Very often
Give you a valuable perspective for making sense of the world around you?	○	○	○	○	○
Help you figure out the best option when taking an important decision?	○	○	○	○	○
Foster a greater appreciation of some aspect of the world around you?	○	○	○	○	○

Some people would say that science and art have nothing in common, while others would argue that they are both human ways of knowing, more similar than they are different.

What would you say?

They have nothing in common.
They have very few things in common.
They have some things in common.
They have a great deal in common.
They are essentially the same.

Please, briefly explain your response to the last question.

Appendix G

Interview Protocols

Interview Protocol P5

Before we begin, I would like to ask for your permission to record the audio of this interview so I don't miss anything you say. Do you provide your consent for the audio of this interview to be recorded?

1. In the second survey you wrote that the intervention portrayed science as "more interesting than you previously thought" to a very large extent.

You added **(A)**:

> I had previously never considered the idea of scientist being emotional when it comes to their or other scientist work. So visually learning about a scientist that was so broken up by a method that he would write poetry about it was very interesting and enjoyable.

Can you tell me more about that?

(Possible follow ups: Why did that make science seem more interesting to you? What played a role in making it enjoyable? *They might mention how it affected them as a future teacher, if so could be interesting to ask them to elaborate on that, maybe ask how that vision contrasts with their experience as a learner?*)

2. About the role of emotions in science, after the intervention you highlighted the role of emotions as a source of motivation. You wrote **(B)**:

> Personally I believe that personal feelings and science will always be linked together, simply due to the fact that we as people are intrinsically tied to our emotions. As **its these emotions that give us the drive and motivations to seek out the different elements curiosity that are inherent in science.**

However, before the intervention you stressed the effects of biases, you wrote **(C)**:

> I feel as though as a scientist one should (to a certain extent) be able to put their emotions and personal biases aside when collecting data and performing experiments. however, its only possible to completely do so. because of this there will always be a level of personal bias within science.

Can you tell me more about how you perceive the role of emotions as connected to bias in science? How do you think scientists should ideally address bias? How about motivation, is that something you had considered before?

3. I noticed you did not answer one of the questions in the pre-intervention survey, that asked you to compare two positions, namely **(D)**:

Some people say that good scientific research is completely objective in that there is only one right and rational interpretation of the evidence, so that the personal taste of a good scientist is completely irrelevant to their work. Others say that the evidence gathered by scientists have multiple plausible interpretations, and that good scientists rely on their personal taste and intuition to choose between alternative interpretations of the evidence.

I would like to know if you recall why you did not complete the question. Is there anything about the question that made it confusing?

4.You wrote that the intervention increased to a large extent how often you think about the concept of energy in your everyday life. Is there any particular example you could share of a situation when you thought about the concept of energy since the intervention, and where you don't think it would have come up before?

5. Are there any changes you would like to suggest about any aspect of the intervention that would have made it more meaningful or effective for you?

Interview Protocol P13

Before we begin, I would like to ask for your permission to record the audio of this interview so I don't miss anything you say. Do you provide your consent for the audio of this interview to be recorded?

1. In the second survey you wrote that the intervention portrayed science as "more interesting than you previously thought" to a large extent.

Can you tell me more about that?

2. About the role of emotions in science, after the intervention you wrote **(A)**:

> I think it is a mix of both it's not necessarily a bad thing either. **If a scientist it passionate about their work of course their emotions might spill in but as long as the work and process is done correctly I think it's fine.**

Can you elaborate on that? (Can you tell me more about what you mean "the work and process [being] done correctly"?)

However, before the intervention you stressed the effects of biases, you wrote **(B)**:

> I think people have implicit bias towards different things. And that it could play a role in the outcome of scientific studies and research. I think we can look back in history and find evidence of this. It's not right and I think science should be unbiased but people aren't and it can taint outcomes.

Can you tell me more about how you perceive the role of emotions as connected to bias in science now?

3. About the role of personal taste in science you wrote **(C)**:

> I think science has a process and must be objectively peer reviewed to make sure nothing is skewed.

Can you tell me more about that? (How do you perceive the role of the individual scientist in making sure “nothing is skewed”?)

4. In the pre-intervention you wrote **(D)**:

> I think that’s human nature plays a role in how we interpret things. For the most part especially nowadays I think that scientists do not let their personal taste get in the way and take large measures to make sure their personal taste does not affect results. At least I hope anyway

Can you elaborate on what you mean by that? Were you drawing a distinction between how scientists interpret results and what results they gather through inquiry?

5. You wrote that the intervention increased somewhat how often you think about the concept of energy in your everyday life. Is there any particular example you could share of a situation when you thought about the concept of energy since the intervention, and where you don’t think it would have come up before?

6. Finally, are there any changes you would like to suggest about any aspect of the intervention that would have made it more meaningful or effective for you?