Chapter 15
Inclusivity in the Education of Scientific Imagination

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Abstract Scientists imagine constantly. They do this when generating research problems, designing experiments, interpreting data, troubleshooting, drafting papers and presentations, and giving feedback. But when and how do scientists learn how to use imagination? Across 6 years of ethnographic research, it has been found that advanced career scientists feel comfortable using and discussing imagination, while graduate and undergraduate students of science often do not. In addition, members of marginalized and vulnerable groups tend to express negative views about the strength of their imaginations and the general usefulness of imagination in science. After introducing these findings and discussing the typical relationship between a scientist and their imagination across a career, we argue that reducing the number or power of active imaginations in science is epistemically counterproductive. We suggest several ways to bring imagination back into science in a more inclusive way, especially through courses on imagination for scientists, good role models, and exemplar-based learning.

Keywords Imagination · Creativity · Science education · Inclusive education · Virtue epistemology · Ethics of science education

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15.1 Introduction

Educators are supposed to provide people with skills that help them in life. Creativity is such a skill. How can educators increase it? Philosophers typically portray creativity as the ability to produce ideas that are both *new* and *valuable*. How do you teach someone to produce a new, valuable idea? For a start, they will need some relevant background knowledge, experience, and especially *imagination* (Gaut 2003; Hills and Bird 2019; Stokes 2014; Stuart 2020). Indeed, the connection between imagination and creativity is so tight that scientists often use them as synonyms (Sánchez-Dorado 2020; Stuart 2019c).

So, if we want to improve creativity, we can start by improving imagination. But how do we do that? The answer depends on what imagination is. Some philosophers argue that imagination is a mental attitude that we take toward some content (e.g., Currie et al. 2002; Arcangeli 2017; Nichols 2006; Kind and Kung 2016). For example, we might believe, doubt, desire, or imagine that we have won the lottery. Belief, doubt, desire, and imagination are different mental attitudes we can take to the same content. They are different, at least because they have different functions: believing we have won the lottery might cause us to jump and down, desiring to win the lottery might cause us to buy a ticket, and imagining that we have won the lottery might only cause a smile. However, if imagination is just one kind of mental attitude that we can have toward some content, it is not clear how it could be improved: we either take that attitude towards some content, or we don't. A promising new view is that imagination should be understood as an *ability*. This is a useful view for a discussion about education because abilities can be improved (Kind 2020, 2022; Stuart 2019b). Insofar as educators do (and should) aim to develop scientific creativity, then they do (and should) aim to develop the *ability* of scientific imagination. "Attending to the workings of imagination is not a soft option" (Midgley 1992, 24).

It was noticed already more than a century ago (Ribot 1906) that there is very little literature on imagination in science education. This continues to be true today (though see Hadzigeorgiou 2016 and Eijck and Roth 2012). Drawing on qualitative observations performed in five research laboratories (all of which contained graduate students, undergraduate students, or both) and interviews with 13 scientists, we claim that while scientists recognize a need to foster imagination in their students, no standard recognized methods yet exist for teaching the skill of imagination (Stuart 2022a).[1] In general, scientists do not talk about imagination. Here are a few indicative quotations from established scientists: "It's not something that people talk about" (interview, PI, 19/06/2019). "Everybody imagines, but no one really talks about it, or how to do it better, or when to spend time on it" (interview, postdoc, 22/04/2019). "I think the only time when I have this discussion is when PhDs

[1] While this paper builds on the results of Stuart (2019c, 2022a), all quotations given are presented here for the first time unless otherwise indicated. For more information on the sociological methods used to collect and analyze these quotations and observations, see (Stuart 2019c).

transition towards postdocs, or postdocs transition to a point where they need to get their own funding. So, where they have to come up with their own research ideas. And that's when I had this discussion where people were scared that they wouldn't have the imagination to come up with these ideas. So I think that's the only point in time" (interview, PI, 19/06/2019).

Of course, scientists do eventually learn to use imagination. They must. But how they do this greatly depends on their individual preferences, abilities, and values, as well as the research culture of their field, which determines the kinds of problems that need to be solved and the methods used to solve them. Also important are the experiences, preferences, abilities, values, and teaching styles of their educators. These can vary dramatically, such that even in a single department, there can be very large differences between attitudes that principal investigators (PIs) take towards imagination-use, and these differences tend to be reflected in pedagogical practices (Stuart 2019c, 2022a).

While imagination is not taught explicitly in science classrooms or laboratories, it is still important to identify how it is taught *implicitly* across the different sciences, educational stages, and geographical locations. Meanwhile, raising awareness about this vital part of science education can prompt educators to think about it more directly, which can lead to the identification and dissemination of successful strategies. This will take time. However, even with the little information we have, we can already show that the existing processes of teaching imagination (whatever they are) are not maximally inclusive.

Why? Despite all the differences in attitudes and approaches to imagination across the labs observed, one thing seems to hold everywhere: whether a scientist values imagination and whether they feel confident in using their own imagination, depends not only on career stage, but also on whether someone is a member of a traditionally marginalized group. People from such groups (whether based on race, gender, ability, etc.) tend to feel that imagination is less important in science, and they tend to have less faith in the strength of their own imagination as compared to non-marginalized people at the same career stage (Stuart 2019a). Statements like the following are common.

> I was just thinking how there is this absolute requirement to be imaginative, to get paid, because you have to come up with a new idea to get the funding, to have a job. And that's really hard because I don't feel like I'm an imaginative person, I tell everyone I'm not very creative, and I compare the two words quite a lot. So yeah, I find it really hard to come up with new ideas because it's something I've never had to think about before…You have these constraints: you have to be imaginative to do something new, but it has to be, whatever the idea is, it has to be able to be studied within a restricted timeframe, and the restricted amount of funding. So you have to come up with something creative that ticks all of those boxes, and that's really hard! I have no idea how to do that! (interview, Ph.D. student, 14/01/2020)

This was a female Ph.D. student whose imagination had already brought her great scientific success. This kind of sentiment appeared regularly for members of marginalized groups, and it was stronger in those who found themselves at the intersection of the more vulnerable end of the sex, gender, race, geographic, age, and career stage continuums. Those at the other end of those continuums often expressed the opposite sort of view: their own imagination was powerful and played a central role in their identity as a scientist, and was partially responsible for whatever success they had already achieved. It is not the case that people in marginalized groups *identify themselves* as having different views toward their own imaginations. The point is that sociological investigation reveals that such people tend to have systematically different views. This is something that can only be noticed with a sufficient number of data points.

We do not want to claim that people at the confident end of the spectrum are incorrect about the power of their own imaginations or that any of them specifically are to blame for this state of affairs. Perhaps, given the same privilege, all scientists would agree that imagination is important for science. No implicit or explicit biases were observed in privileged scientists acting against less privileged scientists, and indeed many of the labs were quite diverse in terms of culture, race, gender, sexual orientation, ability, age, etc. So we do not locate the problem here, either. Instead, we hypothesize that it is a systemic educational issue, and so in Sect. 4, we consider systemic solutions.

Before moving on, we should mention that this chapter's topic lies at the intersection of many different literatures, including education studies, philosophy of science, ethics, gender and race studies, and cognitive science. Particularly important are the feminist (Arámbula-Greenfield 1995; Barton 1997, 1998; Hussénius et al. 2013; Hussénius 2014) and anti-racist literatures on science education (e.g., Anderson and Herr 2007; Dennick 1992; Gill and Levidow 1987; Hines 2007; Law 2017; Kishimoto 2018; and the contributions to the present volume), as well as the discourse on imagination in non-scientific educational contexts (e.g., Rorty 2009; Hatt 2022; Wright 2021; Dewey 1980; Murdoch 1994, 2001; Greene 2000; Nussbaum 1998). A complete understanding of the issues we are going to raise requires insights from all these fields, which we will discuss as we go, as best we can. However, neither of the authors of the present paper are scholars in education studies. One is a philosopher of science interested in scientific imagination, and the other is a scientist who shares an interest in imagination. As we both are passionate about education and the ethics of science, we decided to combine our perspectives in a spirit of interdisciplinarity in a way that we hope is useful, making no claims to completeness or general authority.

15.2 No Imagination Allowed

Scientists approve of the use of imagination in contexts where the usual methods have already failed (or would fail) to provide a solution to a maximally specific problem (Stuart 2019b). More generally, imagination is crucial in periods of uncertainty, whether that uncertainty pertains to a contradiction in the background literature, how to design or interpret an experiment, how to write up a result, how to reply to reviewers, or how to give a presentation. Summarizing interview data from 63 scientists, Schickore and Hangel (2019) show that scientists are often uncertain about these kinds of things. In other words, scientists very frequently find themselves in contexts where imagination is helpful for resolving specific problems.

Education should prepare future scientists for this by preparing their imaginations. This is not currently at the top of the science education to-do list, which is understandable: scientists must also learn the techniques and theory of their domain before imagining how to transcend these. So, we should expect that imagination will not be the main focus in early periods of science education. Still, scientists interviewed agree that the majority of their experiences pursuing undergraduate degrees in science or engineering sharply discouraged the use of imagination (Stuart 2019c). And while we might think that imagination is eventually taught or nurtured in graduate school, this is only sometimes true, and when it is, it can be too late. The endurance test that is science education does not perfectly select for good future scientists. It pushes away many who might have been great. Consider the following reflections of famous physicists David Peat and David Bohm.

David Peat:

> As far back as I can remember, I was always interested in the universe. I can still remember standing under a street lamp one evening—I must have been eight or nine—and looking up into the sky and wondering if the light went on forever and ever, and what it meant for something to go on forever and ever, and if the universe ever came to an end…These sorts of ideas continued right through school, along with a feeling of the interconnectedness of everything. It was almost as if the entire universe were a living entity. But of course, when I got down to the serious business of studying science at university, all this changed. I felt that the deepest questions…were never properly answered…Instead, we were all encouraged to focus on getting concrete results that could be used in published papers and to work on problems that were "scientifically acceptable." (Bohm and Peat 1987, pp. ix–x)

David Bohm:

> I, too, felt that kind of wonderment and awe in my early days, along with an intense wish to understand everything, not only in detail but also in its wholeness.
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> However, in graduate school...I found that there was a tremendous emphasis on competition and that this interfered with such free discussions. *There was a great deal of pressure to concentrate on learning formal techniques* for getting results. It seemed that there was little room for the desire to understand in the broad sense that I had in mind…*Although I was quite capable of mastering these mathematical techniques, I did not feel that it was worth going on with*, not without a deeper philosophical ground and the spirit of common inquiry. You see, it is these very things that provide the interest and motivation for using mathematical techniques to study the nature of reality. (Bohm and Peat 1987, pp. xi–xiii, emphasis added)

Philosophers of science have commented on this aspect of science education as well. Paul Feyerabend argued that science education "leads to a deterioration of intellectual capabilities, of the power of the imagination. It destroys the most precious gift of the young, their tremendous power of imagination" (Feyerabend 1975, 96–7). He adds,

> Teachers using grades and the fear of failure mould the brains of the young until they have lost every ounce of imagination they might once have possessed. This is a disastrous situation, and one not easily mended…Agreement with science, decision to work in accordance with the canons of science should be the result of examination and choice, and not of a particular way of bringing up children. (160–162)

This situation has also drawn the attention of scholars in education studies, for example, the Imaginative Education Research Group at Simon Fraser University (2001–2015), which included scholars Kieran Egan (Egan and Madej 2010; Egan et al. 2015), Gillian Judson (see, e.g., Judson 2015) and Yannis Hadzigeorgiou (see, e.g., his 2016). Hadzigeorgiou writes, "Teachers often fail to use students' imaginations and creativity in their science classrooms, despite the fact that the 'doing' of science requires much imagination" (2016, viii).

The current way of doing things has negative epistemic effects.[2] Most obviously, imagination and creativity are required to solve scientific problems. Insofar as solving problems is part of scientific progress (Shan 2019, 2022), numbing imagination is regressive for science. Equally significantly, it can reduce the diversity of voices in science by driving away those who strongly value imagination. This is counterproductive because science requires diversity if it wants to make any claim to objectivity. Losing people who are both imaginative and marginalized is worse, because it will often be the imagination of marginalized perspectives that is most valuable in solving difficult problems.

To better understand the problem, in the next section, we shift into the first person and present the story of Hannah Sargeant, one of the co-authors of this paper. Dr. Sargeant is a planetary scientist who works on space instrumentation. The story of any scientist will be winding and personal. Still, the specific relationship between Dr. Sargeant and her imagination reflects the typical experience of many scientists. We present it here to focus the discussion, transition into a more careful exegesis, and motivate some positive proposals. Dr. Sargeant will not focus on her experiences with marginalization but, more generally, lay out the evolving relationship with imagination over a career.

15.3 A "Typical" Relationship with Imagination

15.3.1 Reflections of a Space Scientist

In my early years of school education, when I didn't fully grasp what science was, I was primarily interested in understanding how everything and anything works. This curiosity and sense of discovery are generally nurtured in UK primary education. One other potentially contributing factor to this way of learning is the fact that

[2] There are also negative *ethical* effects, e.g., by introducing unnecessary suffering into the life of scientists. While no less important, we will focus on the negative epistemic effects.

primary education teachers often lack confidence when teaching scientific theories and facts. However, there is a lot of themed working with the overlap of subjects in primary education which means that the humanities and the arts are integrated into other subjects, including science. This way of learning can nurture a sense of curiosity and imagination in students. Imagination is also nurtured when discussing the types of jobs that people have. The idea of becoming an astronaut and being among the stars is celebrated, and you are encouraged to imagine what such an experience would be like. However, as I progressed through to high school, and especially with examinations becoming a more prominent feature in school life, the role of imagination in science classes became diminished. In high school, I learned equations and theories with extremely prescribed and constrained problems to apply them to. Experimental work had a focus on developing lab skills and repeating results to confirm known theories. We would never carry out experiments without expecting a certain result.

Another key point is that imagination is never mentioned or knowingly encouraged in the scientific process. For a long time, I thought that curiosity and imagination were for the arts alone. As someone who was not successful in the arts, I, therefore, believed that I did not have imagination.

As I continued on my path to understanding how the physical world operates, I began my physics undergraduate degree. Here we learned more complex theories and formulas with trickier questions to apply them to. At this point, we were being taught by professional scientists; however, the reality of a professional scientist was not communicated to us, and the problems we were solving were still very prescribed with known solutions. Meanwhile, unbeknownst to us, our teachers were conducting research projects and using imagination to enable scientific discovery and find novel solutions to problems. As an undergraduate, I conducted two relatively small research projects, which were daunting at the time as I would always need to figure out where to start. This knocked my confidence and made me feel like I didn't have what it takes to be a "real" scientist. Solving novel problems was a slow and difficult process, and I often ended up at a dead end with no direction. At this stage, I would ask a professor for help, but that would involve them offering up a solution, and the penny still hadn't dropped that it was imagination that I needed to help me to solve the problem myself. If someone had asked me how I used imagination, I would have said that I didn't. There were no discussions about imagination as part of the scientific process.

After completing my physics degree, I trained as a high school teacher. For the first time, I was asked to make observations and record my opinions. As a "scientist," I thought that opinions were useless and that only facts were relevant. I was left frustrated, losing marks because I didn't develop my own opinions; I wasn't thinking for myself. Looking back, I see how naïve I was and that my education to date had simply been the "rinse and repeat" of applying scientific theories to problems. Imagination and critical thinking had been omitted and devalued.

It was only once I began my masters in Space Exploration Systems that I began to really develop these critical scientific skills. The reality of the scientific process was slowly revealing itself. I was beginning to learn about some of the most cutting-edge technologies and research areas, which importantly also meant I was hearing “we don’t know” in response to my questions. I was finally realising what a scientist does; they sit on the edge of the known and unknown, and they are not just solving problems in which the answer already exists, which was my experience as a scientist-in-training. As part of my studies, we were beginning to look at applications of the scientific theories we had been taught, even theoretically. The problems we were solving were also a lot more complex and open-ended. For example, we completed a large group project looking at the design of the infrastructure for the development of a human-tended Mars base. We could apply the theories of astrodynamics and rocket engine design to the development of a series of space craft and routes and launch windows to achieve this goal. There was no single correct answer, so we were interested in thinking outside the box and innovating to create the most efficient and affordable solution. Instead of dealing with constrained problems (often described as “spherical chicken in a vacuum” problems, where many simplifications/assumptions are made such that the problem is completely unrealistic), we were considering many more variables and real-life scenarios. We had a lot more independence and were forced to think imaginatively. This was challenging without any specific training, in the sense that it was mostly just trial and error and gaining confidence.

The transition to my Ph.D. studies involved a more significant shift to real-world problems and working on actual mission payload design and operation. The pressure was, therefore, significantly higher than anything I’d worked on before. The goal of a Ph.D. is to make a novel contribution to knowledge, and so most of the time, I was trying to solve problems that had never been looked at. Imagination was critical to my Ph.D. studies as I sought the right tools to solve the problems at hand. Sometimes this meant looking at similar problems and combining the methods that others had used, or looking at problems from a different perspective and trying to understand the physical processes occurring at the micro and macro level to improve our understanding of the problem. Generally, the problem-solving process involved a lot of failure. For example, I wanted to perform a reaction in a closed system and use the change in gas pressure to measure reaction rate. However, there appeared to be a loss of gas without any identifiable leaks. It was only when I considered the behaviour of gas molecules in a low-pressure system did I realise that the molecules could be condensing, and so, not in the gas phase at all. To get to this point, I needed the scientific understanding from my undergraduate training and the practical problem-solving expertise of lab mates and supervisors to rule out other causes. After my Ph.D. I worked as a postdoctoral researcher, and at first, I wanted to work on prescribed problems, as I still didn’t feel imaginative enough to come up with new research ideas on my own. As I worked on different problems, new ideas would slowly come. The generation of ideas is accelerated with every new skill I learn, as it is in the overlap of skills/expertise where new approaches to problems are identified. With a couple of years of postdoctoral experience, I am no longer intimidated by the idea of generating my own research themes; in fact, I prefer it to conducting the research plans of others. I finally feel confident in the use of imagination in my work. Interestingly, only after simply discussing with the lead author of this work about the use of imagination in science did I realise how important it is. I now consciously consider how I can utilise imagination in my work and how we can integrate this into scientific education.

15.3.2 Imagined Careers

There are several important points to note about this evolving relationship with imagination. First, imagination is celebrated in early education until the introduction of big standardized tests for entering university all but dissipate that enthusiasm, which is damaged further at the university level by competition and assignments meant to "weed out" certain kinds of student. From the student's perspective, interacting with professors is difficult and often embarrassing, and such interactions do not typically encourage more imagination. Finally, it is nearly impossible to guess what a life of science amounts to until at least reaching graduate school. Most of these story beats will ring true to anyone with an undergraduate science training, especially those not from privileged backgrounds.

Luckily, Dr. Sargeant was able to persist and eventually re-ignited some of her earlier curiosity and imagination. Combined with hearing "we don't know" more and more often in graduate school, she began to use her imagination more and more to find, and then solve, cutting-edge problems. This kind of work became exciting and fulfilling, but the feeling that her imagination was lacking persisted into post-doctoral research when it became crucial to come up with new projects of her own. Dr. Sargeant now feels more confident in the power of her imagination.

One final thing to notice is how the relationship with scientific imagination changes over a typical scientist's career. At first, students imagine what science is about and what it would be like to do science, and they ask imaginative questions about the world. Then, imagination gets sidelined in favour of developing skills necessary to pass standardized tests, solve problem sets, reproduce prescribed experimental results, and find solutions to problems that are "small" enough to solve on one's own. Then, as the projects get bigger and more cutting edge, there is a shift to imagining *together*. Undergraduate education is currently better at weeding out imaginative people than it is at preparing students to use their imagination in finding solutions to open-ended cutting-edge problems, or to imagine together with others.

15.4 Improving Imagination Education

How might educators support the development of scientific imagination? One very basic but crucial step is to address the fact that students come to believe (typically during high-school and undergraduate education) that imagination is not essential for the practice of science. Students do not know what the daily work of a scientist is like, and therefore do not know what role imagination plays, if any, in that work.

To remedy this, we suggest that at the critical juncture when science education pivots from inspiring students to a focus on theory and technique, students must be given a chance to see, first-hand, if possible, what the daily practice of science is like, where that practice includes the use of imagination. Through exposure to this kind of experience, students can recognize the crucial role of imagination for professionals in their art, which helps keep them motivated. Allowing students to appreciate working scientists using imagination in their daily work would enable students to reconceptualize the coming years of theory and technique for what they are: necessary steps on the path to something almost completely different. Professional scientists frequently return to their techniques and theory, but with respect to the role of imagination in their work, their professional life is entirely different from their life as a student. Students of music or art understand this, even at an early stage, because they have exemplars to engage with almost any time they please, via their teachers or online videos. They know that imagination will be valued, because they see and hear it exercised by professionals in their discipline. Students of science typically do not have such exemplars. And this can cause imaginative individuals to lose motivation insofar as they are prevented from recognizing that they are in a discipline that will (eventually) value their imagination, even if, at the moment, their experience in the classroom suggests otherwise.

In sum, educators should do their best to destigmatize discussions of imagination in science at all stages. The typical trajectory of imagination should be explained to students interested in pursuing science, and students should be made aware that their imagination will eventually be valued. Also, more precise language should be developed and employed to discuss the imagination, including the different kinds of imagination and ways that it can be applied. For example, it might be helpful for students to learn that imagination as a tendency to fantasize or think in a completely unrestrained way is different from imagination as an ability to produce pursuitworthy hypotheses.

One way to achieve these goals is by designing and providing classes specifically on the imagination at the undergraduate level aimed at science students, as trialed successfully by Chiodo et al. (2020) for engineering students at the Politecnico di Milano. Among other things, this course required students to reflect on the role of imagination in science, and it was highly valued by students (for a different kind of initiative, see Brown 2020). It might be best for these courses to involve philosophers of science at both the planning and implementation stages (Green et al. 2021; Jaksland 2021; de Regt and Koster 2021; Lusk 2022).

However, it might not always be possible or desirable to dedicate an entire course to scientific imagination. And, for some students, such a course might come too early or too late. Still, it should be possible to have a discussion about imagination in science at any stage.

What else can be done? We now present some original data and analysis drawing from interviews that one of us (Stuart) performed with scientists at the PI level over the past 6 years. Specifically, the following list of strategies has been extracted, where each item was suggested in the context of asking how to help struggling students "imagine better," where the definition of "better" was left up to the scientist. Many of these are recognizable as general pedagogical principles, which would be useful in many different contexts but may or may not speak to inclusivity. As we will see below, a number of general themes underlie these suggestions that we can explore in the context of educating scientific imagination in an inclusive way.

1. Use open-ended prompts. These might include metaphors, thought experiments, visualizations, etc.
2. Increase student self-confidence.
3. Provide good role models.
4. Give students responsibility.
5. Encourage a critical attitude.
6. Encourage discussion, both inside and outside of the lab.
7. Don't be dogmatic.
8. Avoid competitive environments.
9. Encourage everyone to admit what they don't know.

These suggestions fit well with a virtue theoretic account of scientific imagination (Stuart 2022a). In general, virtue theory focuses on the properties of a person as a whole, as opposed to their individual actions or the consequences of their actions. Roughly, virtues are character traits that make someone excellent. These might be traits given to the individual by genetic lottery, like good eyesight, or they might be traits that the person worked hard to develop, like humility, courage, and sensitivity to evidence. A good imagination could be either kind of virtue, so we won't discuss this distinction further. (For a discussion of imagination that separates it into two kinds which correspond to these two kinds of virtue, see Stuart 2019b, and for a more general argument that cognitive processes and virtue theory can be connected in this way, see Ohlhorst 2022).

Virtue theory claims that a good scientist possesses the correct overall balance of traits. For example, a good scientist is neither too skeptical nor too open-minded. This is the right way to be, even if many of actions turn out to be "incorrect" in the sense that they had suboptimal consequences. What is essential for our purposes is that when scientists talk about imagination in pedagogical contexts, they naturally adopt the language of virtue theory (Stuart 2022a), and this seems appropriate given that virtue theory has always had a close connection to education, and yields implementable strategies (Bezuidenhout 2017; Nersessian 2022; Orona et al. 2023), while it can be difficult to see how we might implement competing frameworks capable of defining scientific "goodness" (like deontology and consequentialism) in an educational context (Stuart 2022a).

Applying virtue theory to scientific imagination captures items (1–9) in the above list. Good teachers recognize that virtues cannot be taught but *can be learned*. For example, there are no words an educator can say or actions they can perform that would *make* someone brave. Still, if a person wants to become brave, they can internalize words of wisdom and emulate bravery seen in others to develop their bravery, and in this way, become brave. Equally, we cannot *make* someone a good imaginer with uttered words or demonstrative actions. But, for students who want to be imaginative, we can *set them tasks that require imagination* (this encompasses the above list items 1, 4, 7), we can point to (or be) *good role models* (list items 3, 5, 6, 7, 9), and we can *support the virtues that enable imaginativeness* (items 1, 2, 4, 5, 6, 7, 8, 9).

We will discuss all three of these in some detail, paying attention to whether and how they speak to the issue of inclusivity.

15.4.1 Prompting Imagination with Tools

Lev Semenovich Vygotsky convinced a generation of scholars about the importance of imagination for education, (Vygotsky 1967; for an important precursor see Ribot 1906). Much of the literature we see today focuses on the imagination (very loosely defined) of children (Caiman and Lundegård 2018; Fleer 2015; Egan 1990, 1998, 2005; Bascandziev and Harris 2020; Skolnick Weisberg 2020). In Vygotsky's work, we can see the influence of a Kantian sense of imagination as a faculty required for all meaningful thought, but also the Lockean-Humean sense of imagination as the ability to combine ideas together. Vygotsky noted how imagination changes and develops: at first, a child has only a little experience to draw on, which is a limiting factor. But as they accumulate experiences, they have more to draw on, and their imaginings can grow in complexity. At first, they cannot control their imaginings very well, but as they develop, they learn to do this. Finally, young children have difficulty separating what is imagined from what is believed to be true, but they eventually learn to hold their imaginings at arm's length. Vygotsky also drew attention to the fact that imagination is closely connected with play, language, and thought, and that the nature of this connection also changes over time.

The insights that Vygotsky's work inspired can be extended beyond children and adolescents to the university context. For example, as sophistication with language increases, students speak less about play and more about how they *would* play if they were to play (Gajdamaschko 2005). This coheres nicely with the view common in philosophy of science that models, metaphors, thought experiments, and theories can be thought of as sophisticated games of make-believe, which are not so much played as discussed (Friend 2020; Frigg and Nguyen 2020). It also coheres with the view in science education studies that students shift in their imagination from playing a justificatory role to a merely illustrative or communicative role as they progress into higher education (Özdemir 2009). But rather than portraying models and metaphors as acts of play or games of make-believe, Vygotsky portrayed these devices as *tools* that could assist imagination (along with language, algebra, art, diagrams, maps, blueprints, and so on; see Leont'ev 1997, 22). These tools can empower the imagination, and we should use them to help our students. Diagrams, thought experiments, narratives, models, and so on, work (when they do, see

Stephens and Clement 2012; Bascandziev and Harris 2020; Bancong and Song 2020; McCrudden et al. 2011; Coll 2006) because they require students to exert their imaginative effort. Insofar as the imagination is exercised and practiced, and insofar as feedback is possible, imagination can be trained and improved via these means (Egan 1990, 1998, 2005; Kind 2020; Stuart 2018, 2022b; Hadzigeorgiou 2016).

In sum, one option for improving imagination is carefully using tools that require open-ended imagining. Might this address the lack of inclusivity? Perhaps not. It is possible to develop better tools for marginalized groups, but it is unclear whether or how this could work in practice (Kauffman et al. 2022). For example, there might not be any specific metaphors, thought experiments, or diagrams that work well for only one marginalized group or intersection of groups. And defending the specialized use of tools directed toward certain groups might require making essentializing assumptions about the cognitive, social, cultural, or physical properties of members of those groups, as such assumptions are usually empirically, morally, and politically unjustified given inter-group variation. Of course, we should continue to develop the best tools for imagination education possible and all useful tools should be made available to everyone. However, we do not think the use of educational tools for increasing the power of imagination can on its own address inclusivity issues.

15.4.2 Role Models

As mentioned above, one way to increase the skill of scientific imagination (thought of as a scientific virtue) is by exposure to good role models. For someone who wants to develop some virtue (like courage, open-mindedness, or compassion), exposure to someone who is courageous, open-minded, or compassionate shows them how such a person exercises that virtue in practice. The student copies the behaviour of the role model by acting in similar ways in similar situations until that virtue becomes internalized in themselves such that they know when and how to apply it in general. The same thing can work with imagination. Commonsensically, students trained by a PI that is more vocal about imagination will feel more comfortable talking about and using imagination than students who learn under a PI who is less vocal about imagination.

One problem for developing the imagination is that many students do not have exposure to the right kind of role models until graduate school. They might see other students as role model students and professors as role model teachers, but they do not get to see role model scientists who are actually *doing* science. And this is especially true for *imagination* role models as the imagination of a professional scientist is almost impossible to witness and appreciate without being a professional scientist oneself, because until this point it is rare to encounter other scientists who are actually imagining.

Where might good imagination role models come from? It has been proposed that we can increase student exposure to good role models by telling stories about exemplary scientists (Eijck and Roth 2012). This suggestion has some potential. However, it is easy for a science student, especially one who is marginalized and not fully confident, to read stories about people like Einstein, Feynman, Darwin, etc., and feel that they are not (and will not be) like them. This is at least partially because the kinds of heroes we typically find represented in such stories are Anglo-American or European men from privileged backgrounds.

An exciting number of resources are now available that tell the stories of scientists who represent a more diverse set of people, like chemists Angie Turner King, Dorothy Hodgkin, and Marie Daly, mathematicians Katherine Johnson and Maryam Mirzakhani, astronaut Mae Jemison, astrophysicist Jocelyn Bell Burnell, and many others (see e.g., Bolden 2020; Johnson 2019; Moss 2020; Johnson 2020; Brown 2011; Ignotofsky 2016; Prescod-Weinstein 2021). Exposure to more representative role models would be useful for everyone. We hope these will be added to science curricula and eventually form part of the public understanding of science. However, storytelling still might not be the best way to expose students to good role models, mainly because we think that such exposure should be "in person" as much as possible, as direct contact with role models gives students the ability to receive real-time feedback on their imaginings.

One way to give students in-person access to role models is through joint research projects with professional scientists (see, e.g., Chng and Mei 2020; Nersessian and Newstetter 2014; Richter and Paretti 2009). This practice can provide students with role models that are different from those they merely read about or professors whose daily work is inaccessible to them. Insofar as undergraduates come to be exposed to the uncertainties inherent in cutting-edge scientific work, this kind of exercise can help to show students *that* imagination can be important in the work of science. But this will only be effective to the extent that students (a) get to witness professional scientists in moments of uncertainty who resolve that uncertainty using their imagination and make this clear to the student, and (b) learn that such imaginative problem-solving occasions are common in science. With these conditions fulfilled, this kind of problem-based participatory learning could be a useful strategy. Ideally, the role model should already be educated on how to talk about imagination.

In summary, role models have the potential to ameliorate the inclusivity issues highlighted above, at least partially. Students from marginalized backgrounds could learn earlier in their careers to see themselves as insiders, not outsiders, and learn that imagination matters for doing science. However, storytelling and joint research projects can make things worse by knocking down marginalized students' confidence further, especially when the role models are not selected inclusively. It might take years to overcome and reverse the effects that negative experiences with working scientists can have. And these kinds of initiatives might take place at the wrong time: storytelling typically comes early in education (to spur students to try science), but it is not there to help students who have become disenchanted by the competitive, rote, test-based work in upper secondary and lower undergraduate years. Joint research projects typically take place late in undergraduate education, by which point science education has already alienated many potential scientists.

15.4.3 Supporting Virtues

Over the past 15 years, Nancy Nersessian and her colleagues have performed ethnographic research on several different labs (tissue engineering, neural engineering, computational systems biology, and experimental systems biology). One of the outcomes of this work is a new award-winning educational program that focuses on producing virtuous biomedical scientists (see e.g., Nersessian and Newstetter 2014; Nersessian 2022). Interdisciplinary researchers require several virtues, including cognitive flexibility (to understand problems from multiple perspectives), methodological versatility (to be competent with several different methods), resilience (to deal with constant failure and uncertainty), interactional expertise (to navigate across disciplinary boundaries), and epistemic awareness (to appreciate the norms and values operating in different fields) (Nersessian 2022, 296–298). We have argued that a good imagination is also a virtue that scientists should possess. This virtue is among the most fundamental, as it is helpful or necessary for many of the other virtues that scientists should possess, including the ones just mentioned.

Imaginativeness (like all other virtues) should aim to find a "golden mean" between two extremes. That is, between, on the one extreme, having your head always in the clouds, and on the other, being stuck inside a box. Different PIs have different strategies for helping students find the right balance. Many embrace a negative strategy: "I often just leave students on their own. I'm always very happy to talk to them…but I don't like so much to tell students what to do. Because I think, too much of that stifles their imagination" (interview, 22/05/2019). Another PI in a different field agreed: "I lead them with problems to solve. And I don't try to solve the problem for them" (interview, 08/12/2018). This agrees with a fundamental assumption of most accounts of virtue theory: virtues must be developed through the effort of the student, not only the teacher. To hone the virtue of imaginativeness, PIs might have various (if implicit) strategies that include using open-ended prompts and tools (as discussed in Sect. 4.1) or being a role model for the students (as mentioned in Sect. 4.2). But there is another essential thing that educators can do, and this is to develop the virtues that support imaginativeness, which enable students to perform the actions required to develop imagination.

To do this, educators can discourage competition in the lab, increase a skeptical attitude toward experimental results and theoretical dogma, and foster a supportive environment in which people can feel safe to fail and admit that they don't know something, and to joke around. These kinds of changes support scientific virtues like courageousness, kindness, honesty, resilience, and curiosity.[3] We think there is one virtue that is required for many of these, and that is self-confidence (sometimes called intellectual courage). When asked about imagination, the words of marginalized scientists unequivocally point toward a felt lack of self-confidence. Research on the effects of marginalization shows why this is to be expected. Someone is marginalized when they are on the margins of a culture, social group, or power structure (Billson 1988). Whether this is explicit to them or not, marginalized people tend to have less control over the determining factors of their lives, fewer available resources, and fewer opportunities. This naturally leads to lower confidence and self-esteem (Burton and Kagan 2003). Always being perceived as "other" or different, and always wondering about tokenism, bias, and stereotyping "is suffocating" (Nugent et al. 2016). It can produce an amplified and exclusive focus on one's negative traits or failures, as well as a greater felt need to justify oneself as belonging.

In the case of science education, low self-confidence has at least two negative consequences for the development of imagination. First, it can make a student feel that insofar as imagination is required in science, they are not going to be someone who will be very imaginative, which might also make them less prone to try. As Lin et al. (2015) show, higher extroversion correlates with using imagination to come up with new ideas, and higher motivation correlates with an increased ability to use imagination to draw connections between concepts and achieve goals. The combination of motivation and a safe social climate together strongly predicts whether imagination will be used at all. As marginalization is an aspect of social climate that can reduce extroversion and motivation, the development of imagination will suffer in social climates that include marginalizing factors (which is, unfortunately, most social climates). Second, a marginalized student will feel a greater need to prove that they are a good scientist who belongs to the social group as much as their colleagues do. Insofar as their image of a good scientist does not include using imagination but instead things like mathematical and technical competence, they will downplay any reliance on the imagination in favour of mathematical and technical skills (Stuart 2019a, c).

Finally, confidence typically drops when entering a new career stage, e.g., from undergraduate to graduate school or graduate school to postdoctoral research. And this drop will disproportionately affect marginalized students. Confidence typically rises when accumulating experience in solving problems. But this will be less pronounced for marginalized students. How can we raise confidence in marginalized students overall? Common suggestions include increasing the representation of

[3] We thank Elisabeth Hildt for prompting us to think more about curiosity, especially in light of the discussion in Sect. 3.1. There is precious little work in philosophy of science on curiosity (Inan 2017; Inan et al. 2018; Papastephanou 2019; Miščević 2020). The way we see the connection between creativity, imagination, and curiosity is as follows. Taking up a virtue-theoretic stance, creativity can be understood as the disposition to use (and be motivated to use) imagination to generate new and valuable ideas and to see those ideas through (this is inspired by, but distinct from, the account presented in Hills and Bird 2019). That motivation to find new ideas and see them through is the effect of curiosity, which might be portrayed as a desire for understanding (Miščević 2020).

marginalized people among faculties and in syllabi, changing funding structures that keep marginalized people out of academia, eliminating targeted surveillance of marginalized students, addressing inequalities resulting from school districting, increasing access to the internet, and improving teacher preparation. Reasons have been given to support these measures elsewhere, which we will not rehearse here. Insofar as they are effective, they would reduce marginalization and the negative effects that marginalization has on self-confidence.

15.5 Conclusion

Imagination is necessary for science, and a good imagination makes good science better. Current trends in scientific pedagogy and elsewhere conspire to hide the role of imagination in science from students, and also to make the education of imagination less inclusive than it should be.

In this chapter, we have tried to provide a map of the changing relationship scientists have with their imaginations over the course of a career, and canvassed several ways to improve the current situation. These include: providing courses on imagination to scientists that could give students a better idea of the role of imagination in the daily work of professional scientists, and new language to discuss scientific imagination; using open-ended tools that require students to use their imaginations, including thought experiments, models, and metaphors; exposing students to role models, whether through storytelling or (better) in person via joint research initiatives; and finally, supporting the virtues that are needed to have confidence in one's ability to use imagination, by discouraging competition, encouraging healthy skepticism, and fostering an environment where people feel safe to fail and play. Perhaps the most critical positive suggestion, which we also think is relatively easy to put into practice, is setting up an exemplar-based learning system where students get to occasionally see the daily work of scientists, and the use of imagination in particular, which is important insofar as it would help imaginative students stay motivated by understanding that the theory and technique they are learning are actually stepping stones to a future time at which their imagination will be highly valued.

There are many more topics we could discuss regarding imagination and scientific education. We will mention just three. Almost every scientific discipline is now thoroughly interdisciplinary. Are there special challenges when teaching students how to imagine in an interdisciplinary way? Second, there is a close connection between (certain kinds of) imagination and emotion (Arcangeli 2017). Emotion is also essential in science (Kozlov 2023), though it is not as well discussed as it should be in the education literature (Weil 2002). Can this connection be used in a positive way to assist in the development of scientific imagination in students? Finally, scientists are now using tools like artificial intelligence to help them extend the power of their imagination. How might this change what is required from the imagination of future scientists, and how can we prepare them for this in advance?

We think there are bound to be connections between all three issues and the inclusivity of the education of scientific imagination. Thus, there is still very much to be done. We hope the imaginations of scholars will be up to the task.

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