The Qualitative Study of Scientific Imagination

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Abstract

Imagination is extremely important for science, yet very little is known about how scientists actually use it. Are scientists taught to imagine? What do they value imagination for? How do social and disciplinary factors shape it? How is the labor of imagining distributed? These questions should be high priority for anyone who studies or practices science, and this paper argues that the best methods for addressing them are qualitative. I summarize a few preliminary findings derived from recent interview-based and observational qualitative studies that I have performed. These finding include: (i) imagination is only valued for use in addressing maximally specific problems, and only when all else fails; (ii) younger scientists and scientists who are members of underrepresented groups express less positive views about imagination in general, and have less confidence in their own imaginations; (iii) while scientists seem to employ various epistemological frameworks to evaluate imaginings, overall they appear to be epistemic consequentialists about imagination, and this holds also for their evaluations of the tools they use

to extend the power of their imaginations. I close by discussing the epistemic and ethical consequences of these findings, and then suggesting a few research avenues that could be explored next as we move forward in the study of scientific imagination.

Introduction

1. The study of imagination

The goal of this paper to motivate the qualitative study of (scientific) imagination, gather together all my own qualitative research results on scientific imagination in one place for the first time, and draw attention to exciting open research questions in the vicinity. We begin with a brief history of work on the imagination, before shifting into the topic of scientific imagination in particular. Then, I argue that qualitative research in the area is necessary, and collect the results of recent qualitative studies that I have performed on scientific imagination. We finish by proposing some open questions.

First, some background. The imagination is one of our most interesting, and most human traits. It has been an important focus of study for millennia, but it has never received such prolonged and undivided scholarly attention as it is getting right now. These days, studies in psychology focus on the development of imagination in children,[1] subtypes of imagination such as counterfactual reasoning,[2] and imagination in non-human primates.[3] A search on JSTOR turns up almost a million results on the topic, and online archives in philosophy, social science, and cognitive science each locate thousands of entries with "imagination" in the title, most of which were written in the last decade.

[1] E.g., Mitchell (2002), Aguiar et al. (201), Caiman & Lundegård (2018), Lillard (1993), Harris et al. (1994), Weisberg et al. (2013).
[2] E.g., Mandel et al. (2005), Byrne (2005).
[3] E.g., Savage-Rumbaugh & McDonald (1988), Matsuzawa (2020), Jensvold & Fouts (1993), Mitchell (2002).

Looking back, there are a number of recent developments that make the current emphasis on imagination seem inevitable. Here are a few (the first three are inspired by Kind 2018):

1. The mental imagery debate of the early 1980s concerned how mental images were represented in the brain, specifically, whether this was done by imagistic or non-imagistic representations. This naturally led to a discussion of visual (and more generally, *sensory*) imagination (Arditi et al.,, 1988; Kosslyn et al.,, 2006; Pylyshyn, 2002; Dennett, 1981).
2. The publication of *Naming and Necessity* by Saul Kripke (1980) refocused a large subset of philosophers working on metaphysics and language. One question it inspired is still a major topic in modal epistemology: What does our (in)ability to imagine things tell us about the (im)possibility of those things? See, e.g., Yablo (1993), and Gendler and Hawthorne (2002), Gregory (2010).
3. Kendall Walton's influential book *Mimesis as Make Believe* (1990) portrayed fictions as sets of implicit and explicit prescriptions to imagine. Since many things can fruitfully be described as fictional (including numbers, idealized physical systems, mental states, the average family, etc.), many applications outside of aesthetics have been found and explored, and this framework continues to be popular in several subdisciplines of philosophy.
4. Memory has always been an important research topic in psychology. A persistent question (at least since Hume) has been what makes something a memory as opposed to a "mere" imagining. Causal connectionists claim that something is a memory if the mental experience was caused (in some appropriate way) by the events that make up the content of the memory. A popular account of memory introduced by Suddendorf and Corballis (1997) now claims that remembering is just imagining about the past. New accounts

based on this idea defend a certain temporal symmetry of thought such that there is no difference between memory about the past and thinking about the future: both are "mental time travel" (see, e.g., Berg et al., 2021; Adam Bulley, 2018; Klein, 2013; Suddendorf, 2010; Suddendorf & Corballis, 1997).

5. The recent discovery of the aphantasia-hyperphantasia spectrum is revolutionizing the study of imagination (Dawes et al., 2020; Liu et al., 2023; Whiteley, 2020; Zeman at al., 2015; Zeman et al., 2020). This continuum ranges from those who are unable to voluntarily imagine sensory content when prompted (aphantasia), to those who are unable to prevent themselves from imagining a great deal of sensory content when prompted (hyperphantasia). The consequences of this discovery are only beginning to be unpacked.
6. Empathy plays a large role in human social life. Cognitive scientists and philosophers have all but rejected the idea that we empathize with other people by constructing theories about them, in favour of a view according to which we use imagination to simulate what other people feel and think (Morton, 2013; Schmetkamp & Vendrell Ferran, 2020; Sherman, 1998; Stueber, 2011; Currie & Ravenscroft, 2002). If correct, this puts imagination at the heart of our social lives.
7. Researchers in machine learning have attempted to code various kinds of cognitive faculties into programs designed to better approximate (or outdo) human reasoning. Some of those are specifically meant to replicate and replace human imagination (Wong, 2022; Chandrasekharan et al., 2013; Stuart, 2019a; Halina, 2021). At the same time, we might think that imagination is the one ability that most clearly separates machines from humans.

8. The concept of social (and sociotechnical) imaginaries, introduced by C. Wright Mills in 1959 and powerfully revived in 2009 by Sheila Jasanoff and Sang-Hyun Kim, has become very influential in social science and science and technology studies. An imaginary is a social structure composed of joint imaginings of social life and order, which can be used to explain many things, including money, gender, race, technologies, nation-states, and society itself (see, e.g., Mills, 1959; Jasanoff & Kim, 2009; McNeil et al., 2017; Sismondo, 2020).

While imagination allows us to leave reality behind, it also enables us to grasp how the world is. This is especially clear in science, where imagination forms a core component of scientific method, and yet, paradoxically, delivers its valuable inputs without interacting directly with the targets of study. Classic studies on the topic emphasized the importance of imagination for science education (Vico, 1730; Ribot, 1906; Vygotsky, 1997) and historical work highlights the pivotal role played by imagination during major scientific revolutions (Holton, 1978; 1996; Jacob, 2001; Hadamard, 1945; Rocke, 2010; Taylor, 1967). Reading through these case studies gives a strong impression that “the white heat of imagination” is woven deeply into the fabric of science’s own self-image (Taylor, 1967, pp. 4-5). But how does it work?

In more recent philosophical work, scholars have discussed the different kinds of imagination present in scientific thought experiments (Arcangeli, 2010; 2017b; 2018; Meynell, 2014; 2018; Murphy, 2020; Stuart, 2017; 2019b; 2022b), the role of imagination in scientific modelling (Frigg, 2010; Salis, 2020; 2021; Salis & Frigg, 2020; Toon, 2012), the role of imagination in scientific theorizing (French, 2020), and much else (see, e.g., the entries in Levy & Godfrey-Smith, 2019). Despite all this, there has been little methodological discussion on how we should go about studying the scientific imagination.

2. Why we need qualitative research on scientific imagination

Although things are changing, the preferred method of philosophers is usually to stay in the armchair. In the worst case, philosophers commit the mistake Ian Mitroff identified in 1974: “Philosophers of science do not hesitate to make all kinds of universal statements about the nature of science based on no empirical data at all, or worse yet, on the empirical data of what in their imagination they construe as the behavior of scientists” (p. 269). A more responsible way for philosophers to avoid getting their hands dirty is to do what is sometimes called “empirically informed” philosophy of science. This involves building on empirical insights (usually from psychology and neuroscience) relevant to a specific philosophical issue. (For worries about how this strategy is employed in practice, see Yan & Liao, 2023). However, since there is almost no existing empirical data on scientific imagination-use, this kind of empirically-informed philosophy of scientific imagination is presently impossible.

Nevertheless, someone interested in scientific imagination might fruitfully apply existing insights gained on *non-scientific* imagination to scientific imagination. Despite requiring some guesswork, this strategy can be successful when done carefully. Alison Gopnik has argued that scientific thinking is an expression of natural tendencies we see in children (1996), so we should expect that at least some findings about childhood imagination will apply to scientific imagination. For example, in a recent book called *The Scientific Imagination*, three chapters were written by psychologists, and two of them draw plausible conclusions about scientific imagination from studies on children (Skolnick Weisberg, 2020; Bascandziev & Harris, 2020). The other chapter draws on studies performed on non-scientists (Lombrozo, 2020), and is equally informative.

This kind of approach might accurately predict many contours of the scientific imagination. But we should not expect it to predict all of them, as there will be facts about the scientific imagination that we could not be guessed, even given complete knowledge about the non-scientific imagination. This is because becoming a scientist requires long years of complex professional training and socialization, and experiences undergone during this time will have consequences for how a scientist understands, uses, evaluates, and teaches scientific imagination. Just as it would be interesting to discuss the special kinds of imagination developed by artists, judges, engineers, and architects, it is interesting to discuss the imagination of scientists.

Perhaps the most popular way to reject the need for empirical evidence in philosophy is to appeal to the nature of philosophy itself, for example, by claiming that philosophy is a purely normative enterprise whose main focus is to tell us how things *should* be, rather than how things are. On this view, philosophers learn about truth, goodness, knowledge, beauty, meaning, existence, and so on, and with accounts of these in hand, they can produce concrete recommendations for scientists (and everyone) that will hold no matter what. As far as I know, there aren't any philosophers who defend such a strong view. Still, it is important to remind ourselves to stay away from this kind of thinking by pointing out how difficult it is to say what ought to be without relying on detailed information about what is. Of course, the opposite mistake is possible: deriving normative conclusions carelessly from descriptive information. For example, just because scientists evaluate uses of imagination in a certain way does not mean that they ought to. Caution is required: the goal isn't to identify the norms that scientists use and then engrave them on stone tablets. Instead, we should seek a middle ground where bottom-up and top-down methods meet. "Bottom-up" here refers to data-centric approaches that use empirical methods to extract the norms that govern actual scientific practice, and bring them to light for scientists and others to analyze and improve, for example, by identifying and resolving conflicts between norms of imagination, or between those norms and other epistemic or ethical values that scientists hold. "Top-down" approaches produce high-level conclusions about the nature of certain values and then attempt to bring these to bear on scientific activity.[4]

A different kind of objection would allow philosophers to draw on empirical data, but not *qualitative* data. Perhaps we prefer quantitative data for grounding normative recommendations as it is more generalizable. Qualitative research findings cannot be generalized, so the objection goes, and therefore it cannot ground normative claims. However, qualitative research can be normative even if it fails to generalize. Many feminist scholars, race scholars, and critical theorists, for example, use their findings explicitly to improve the standing of groups that suffer from oppression, without feeling any need to generalize their findings to other groups, whose oppression arises or manifests itself in different ways. Combining qualitative research with activism in this way is increasingly seen as legitimate, and it can also be used to improve science, which is a social practice that is not free from oppression. That is, non-generalizable findings can still be used to propose new (contextually-relative) best practices.[5]

Secondly, the idea that qualitative research is not generalizable needs to be qualified (Osbeck & Antczak, 2021). There are sometimes contexts in which qualitative findings *can* legitimately be extended to other subsets of a population, or other groups. Science is one of those contexts because of its homogeneity, which is undergirded by a relatively consistent set of norms and values shared by an international community of scientists, as well as by the fact that most

[4] Of course, in practice, bottom-up and top-down approaches rely on (and inform) one another all the way through. The point here is just to remind ourselves that a purely top-down approach would be neither effective nor complete.
[5] These points about normativity may seem obvious, but they are important for a practical reason: philosophers who do qualitative research often have a difficult time publishing their research in philosophical journals, as reviewers do not see the research as having any normative implications. It is therefore dismissed as "mere" sociology or psychology. It is good to have ready replies to such worries.

laboratories consist of scientists from all over the world. That is, for most things, scientists believe there should be no difference between Malaysian science and Korean science and Swiss science, in the sense that any cultural peculiarities, if found to be epistemically productive, should be communicated and integrated into all other labs working on the same topic. Because of this, qualitative findings about science are often generalizable when they produce normative recommendations.

To understand scientific imagination we must go beyond studies on non-scientists, and qualitative research methods cannot be dismissed. But *which* qualitative methods should be used? One possibility is historical methods, including oral history. These are useful methods, and indeed, some of the first monographs on scientific imagination employed them (Holton 1978; Rocke 2010; Hadamard 1945). Autobiographical notes, marginalia, correspondence, and oral history can shed light on what was happening in the minds of scientists, and this continues to be a valid and useful way to study scientific imagination.

However, it was recognized already half a century ago that some questions about science cannot be answered through the use of historical methods alone. In a two-page essay, L. Pearce Williams (1970) made this point concerning the disagreement between Karl Popper and Thomas Kuhn, writing that “the history of science cannot bear such a load at this time” (p. 50). Instead, “the scientific community may be treated like any other community and subjected to sociological analysis. Note that this ‘may’ be done, but that it has not yet been done…To repeat, we simply do not have this information” (p. 49). Similar calls to sociological action would be repeated soon after (e.g., Mitroff, 1974; Feyerabend, 1975), and continue to the present day.

Nevertheless, qualitative methods are still not commonplace in philosophy of science, and too many philosophers are tempted by what Ian Mitroff (1974) calls the “storybook” image of science that is popularized in scientific articles, textbooks, press releases, and by scientists themselves (p. 9). Luckily, things are beginning to change. It has never been easier for philosophers of science to learn to use qualitative methods,[6] as there are more and more good exemplars to be found within the discipline (Buddle et al.,, 2021; Dunbar, 1995; Ivanova et al., 2023; Leonelli, 2008; 2016; Nersessian, 1992; 2008; 2022; Ritson, 2021; Ankeny et al.,, 2022), and many courses and workshops run by experts in the use of those methods. Also, old disciplinary boundaries separating philosophy of science from "rival" fields in which one finds qualitative methods used (such as science and technology studies and the sociology of science), are slowly eroding. Finally, quantitative methods are growing in popularity in philosophy of science, and this can have a gateway effect, opening avenues for the acceptance of empirical methods generally, and qualitative methods as well (for more on the history of ethnographic methods for philosophy of science, (see Nersessian & MacLeod, 2022; Nersessian, 2022, and the other entries in this special issue). With that, I conclude our tour of reasons not to use qualitative methods to learn about scientific imagination. Now, we turn to some positive reasons in favour of taking up those methods.

Imagination as a trait is highly variable, and highly personal. Some people imagine very vividly, while others imagine in a more conceptual way. But these differences can be easily hidden, as discussions drift into vague truisms about the importance of imagination and creativity. To avoid this, qualitative interview methods recommend getting participants to walk the interviewer through recent, past, and possible imaginings, in other words, to focus on specifics. This is complicated by the fact that voluntary sensory imagination is typically less

[6] By this term I mean ethnographic methods, including interview methods and participant observations. There are many other methods that may go by the name "qualitative," including discourse analysis, narrative analysis, and phenomenology.

vivid than unconscious sensory imagination (Blomkvist, 2023), so it is often difficult or impossible to recreate voluntarily in the mind what earlier appeared by means of more vivid subconscious imaginings. In sum, no matter how good interview data is, it is likely not enough.

For this reason, interviews must be combined with field observations in order to triangulate and test the interview findings. However, this creates a new problem: namely, that of identifying uses of imagination in social settings without assuming a specific definition of imagination on the participants' behalf. Of course, this is a common problem for qualitative researchers, who often need to bootstrap themselves up to an analytically useful height all at once. The key is open-ended inquiry that stays flexible: research questions, themes, codes, and hypotheses that appear useful today might have to change tomorrow. Indeed, this is why qualitative methods are currently more appropriate than quantitative methods for scientific imagination: while surveys could be sent out to thousands of scientists by email, good answers only come from good questions, and it isn't yet clear which are the good questions. The best starting point, given that we are still very much at the beginning, is open-ended qualitative inquiry. Only this kind of methodology is able to extract types, features, and uses of imagination used by scientists which are still unknown to researchers.

In sum, we have an interesting context of imagination-use, science, and we do not yet have empirical data about how imagination is used in that context. Until that data is obtained, we can only go so far in our study of the topic. Motivated by this, I performed a number of qualitative studies whose findings will be outlined in section 4. Those findings were not meant to support or disprove any specific claims made in the philosophical or psychological literature; they are merely an attempt to identify some patterns that appear concerning the nature, function, distribution, ethics, and epistemology of scientific imagination.

3. Methodology

The work began with a pilot study (*Study 1*). Five participants were selected from two biology labs. One lab engaged in computational systems biology, while the other was an experimental biology lab. Lab members came and went, but each lab employed roughly 7-10 members at any given time. Observations and interviews were performed over the course of a semester, between January 2016 and April 2016. Two semi-structured, hour-long interviews were performed with each of the five selected participants, with short follow-up discussions after the end of the study. More than 10 hours of interviews were recorded and transcribed, as well as more than 20 hours of observational data from lab meetings, colloquia, and informal events.
A grounded theory approach was chosen for coding and analysis, at least partially because, as we mentioned above, the main concept at issue ("imagination") does not have anything like a settled definition in the literature, and it seemed wise to allow definitions for this term (and related terms) to emerge from the study itself. It was not a pure grounded theory study, however, as some hypotheses were formulated in advance, consistent with analytic induction. All hypotheses, whether they emerged during the study or were pre-formulated, were tested against coded transcripts of the audio recordings of interviews and field observations, and in follow-up interviews.

From the beginning it was assumed that scientists would find it sensible to talk about imagination as a cognitive process, and that they would agree that it plays some role in science. It was also assumed that some scientists might not be very willing to discuss imagination, as it can be seen to clash with the popular image of science as cold, emotionless, and directed purely at truth (McAllister, 2012). Because of this last assumption, no mention was made of imagination to the participants of Study 1 until towards the end of the last interview. In general, the studies attempted to instantiate what Nancy Nersessian calls "cognitive ethnography" which characterizes scientific laboratories as cognitive-cultural communities with epistemic goals, whose histories are important for understanding them (see, e.g., Nersessian 2022). It entails analyzing not just the individual scientists and their behavior, but their on-going historical relations to each other and their environments and tools.

For each participant, the first interview covered relevant personal and academic history, and finished with an overview of the current problems they were working on and the methods they employed to tackle them. The second and follow-up interviews inquired into the daily cognitive work of the scientists, focusing on their reasoning connected with problem-choice, model-building, experimentation, data interpretation, visualization, and paper-writing. Questions were then asked about the roles of mathematical reasoning, emotion, humor, and imagination. 173 individual codes emerged during the coding process, and these were arranged into 12 higher-level themes (emotion, practice, problems, pedagogy, socialization, methodological considerations, personal details, important events, cognitive processes, modelling, visualization, and imagination). Rough connections between the codes were hypothesized to explain the data, which were tested in follow-up interviews (for more information, see Stuart, 2019).

The next study (*Study 2*) was limited mostly to interview protocols. In some cases this was because the scientists worked in institutions where lab visits were difficult or impossible, but in most cases it was because worldwide lockdowns in response to COVID-19 caused several labs to cease their in-person work entirely during the period under study. One lab was a genetics lab, and two were climate science labs. There was additionally one physicist participant, one mathematician participant, and one space scientist. Interviews took place between 2018 and 2022. An important purpose of Study 2 was to investigate which insights (if any) from Study 1 could be generalized, as well as to get a broader view of scientific imagination by looking at different fields of science.

4. Lessons learned about scientific imagination

I will now present some findings based on the above research. These concern the function, distribution, evaluation, and empowerment of imagination. The following mostly summarizes what is discussed in greater detail elsewhere, however, general themes will be pointed out for the first time here, e.g., that most norms governing the use of scientific imagination seem to discourage or limit the use of imagination. Again, the purpose is to showcase recent work at the intersection of philosophy of science and qualitative methodology with the hope that it might spark interest in others.

4.1 The function of scientific imagination

One outcome of Study 1 was that imagination is not universally approved of in science. For example, imagination used for its own sake, as in daydreaming or fantasizing, is generally frowned upon. The only context in which imagination is universally celebrated is in problem-solving. This was confirmed by the interviews conducted in Study 2.[7] What is interesting, however, is that the kinds of problems scientists *claimed* to use imagination to address were not actually the problems they used imagination for. For example, scientists in Study 1 claimed that imagination was important for tackling big issues, like understanding how cells "make sense of" their environments, how to advance cell microscopy, and how to apply insights concerning variable cell responses for medical use. In practice, these questions were not the ones imagination was used to address, because in practice, scientists do not actually attempt to solve

[7] Nersessian's guidelines for cognitive-ethnography include a recommendation to focus on the problem-solving practices of a laboratory. While this recommendation is backed up by Nersessian's own research (not to mention being a priori plausible) it was not assumed that problem-solving would be the context in which scientists explicitly approved of imagination use. That they did is another point in favour of Nersessian's framework.

such problems in their daily work. Of course, imagination *could* be used to think up solutions to big problems like these, but if anything like this actually happened, for example, in a lab meeting, scientists would almost immediately be encouraged to refocus on more specific versions of these big problems. Rather than how to cure cancer, focus on how to deal with a lack of fit between a particular computer model's outputs and some experimental data. In addition, imagination was never used to generate or probe possible solutions to *any* problem except as a last resort, when all other methods had been tried and had failed to produce solutions. In sum, the following norm appears to govern imagination use in science: imagination is only valid for use in addressing maximally specific problems, and only when all else fails (Stuart, 2019c).

There are epistemological considerations in favour of this norm. For one, the human imagination is not very useful when it comes to exploring systems with many variables (Cowan, 2001). It just doesn't have the computing power. By "whittling down" a problem into a maximally specific version, scientists eliminate potentially confounding variables one-by-one. They are not explicitly trying to make the problem more tractable for the imagination, but in effect, that is what happens. A second reason in favour of this norm is that the more specific a problem becomes, the more background knowledge is brought to bear, which means there are more constraints on the imagination. Most authors in the literature on imagination agree that constraints are necessary for imagination to produce new knowledge, and the more constraints, the better (see, e.g., the entries in Kind & Kung, 2016. For a counterargument, see Stuart 2020).

However, the norm also has some potential downsides. The most obvious is that it encourages a conservate attitude insofar as it discourages the use of imagination in questioning established scientific dogma. Of course, some amount of conservativeness is good, and no one would suggest that scientists should spend all their time questioning dogma: this would not be practical or fruitful. Still, a consequence of this norm might be an undesirable *over*constraining of the imagination, which might lead to it being *underused*, which is relevant because all principal investigators interviewed agreed that over-constrained imaginations were much more common that overactive ones. That is a bad thing: we want imaginations that are in between weak and overactive, and it appears science skews towards weak imagination (at the undergraduate and graduate level at least).

4.2 Who gets to imagine?

Another outcome of Study 1 was that attitudes about the importance of mathematical reasoning (very important but neglected in biology), humor (socially very important but scientifically unimportant) and emotion (important for motivation but not valid in scientific reasoning) were extremely consistent among participants, but attitudes towards the importance of imagination varied in a consistent way: younger scientists and scientists who were members of underrepresented groups (including women, certain ethnic minorities, differently abled, or neurodivergent people) expressed less positive, or even negative, views about the usefulness of imagination in science, and more worryingly, they also tended to express negative views about the strength and usefulness of their own imaginations. As a result, such scientists might try to avoid imaginative tasks, or offload them to scientists who were later in their careers or were members of more privileged groups.

This situation has negative ethical and epistemic consequences for science (outlined in Stuart and Sargeant, forthcoming), including pushing more imaginative people out of science, reducing the diversity of imaginative perspectives in science, and again increasing conservativeness in science. This finding was confirmed by Study 2 participants.

There are several possible explanations for this situation. One is that young scientists and those from traditionally marginalized groups face additional pressure, whether due to targeted or systemic oppression, that creates a feeling of “otherness” which can motivate them to leave science, or otherwise feel they must “prove themselves” by developing prowess in more “hardcore” tasks that require experimental, mathematical, or computational ability. But by doing this, those scientists risk siloing themselves away from the imaginative work they might otherwise be doing and developing confidence in the use of their imaginations.

Another explanation for this finding is that science education does not teach students that imagination is a sanctioned – and important – part of the scientific method, or how to use it. This is something early career scientists must learn through experience. However, scientists from more vulnerable groups tend to have less access to personal mentorship and networking opportunities, and as a result, they are not made aware of the validity and importance of imagination in science via mentorship. On the other hand, well-established scientists, especially those in overrepresented groups, praise imagination in general, and their own imaginations in particular, going so far as to attribute major successes to the power of the imagination.

To be clear, nothing malevolent was observed in any of the lab meetings, or during any of the interviews. It seems likely that this kind of imagination-avoidance results from structural features of the way that modern science is taught and organized (Özdemir, 2009). Thus, structural solutions are required. For some proposals in that direction, see (Stuart & Sargeant, forthcoming).

4.3 What counts as a good scientific imagining?

Study 2 participants were asked to provide examples of imaginings that they considered good, and imaginings they considered bad, and to explain the difference. One interesting pattern in their answers was that *how* a scientist defined good and bad imaginings depended on *when* the imagining was posited to take place in time (Stuart, 2022a), that is, whether the imagining in question was located in the past, present, or future.

Imaginings in the past were explained as being good or bad because of the good or bad consequences of those imaginings. Good consequences included new discoveries or new applications of techniques or instruments from outside the field. Bad consequences included wasted time and resources.

Imaginings in the present, e.g., in the context of an on-going attempt to solve an open problem, are judged to be good or bad if they are properly (i.e., *responsibly*) constrained, to the best of the scientist's ability. At first, a scientist will want to obey all possible constraints, like representational accuracy and consistency with background knowledge. But when that doesn't work, some constraints must be broken. In such cases, the operative norm seems to be as follows: break the minimal number of constraints possible, and break the lowest-confidence constraints first. If this doesn't work, higher-confidence (e.g., better established) constraints can be broken, again, one-by-one. Imagining in this way is thought to be a responsible way to proceed (Stuart and Sargeant, forthcoming b).

If the time-index changes to the future, e.g., by focusing on how a scientist would want themselves to imagine in the context of addressing a future problem, they switch from speaking about good and bad imaginings to speaking about good and bad *imagination*. To develop a good imagination, techniques should be used to empower the imagination, e.g., by increasing the size and quality of the experience-base from which the imagination draws, having good colleagues to discuss ideas with, being in the right kind of physical environment, and so on. In these cases, imagination is thought of more like a skill or character trait.

These different ways of evaluating acts of imagination suggest a kind of epistemological pluralism, such that there are different senses of "good" that imaginings can instantiate. However, it appears that scientists ground all their evaluations in good and bad *consequences*. Thus, the rules they recommend, like breaking constraints one-by-one, are justified in terms of their expected good consequences. Likewise, increasing the power of imagination in general is also valued for its expected good consequences.

It is no accident that the kinds of justifications scientists give correspond to the three most popular theories of the nature of justification in philosophy: epistemic consequentialism, deontic epistemology, and virtue epistemology. I did not have these frameworks in mind when analyzing the transcripts of interviews, but as a philosopher, I was aware of them. Still, I was not expecting to find all three used, nor that they would each be associated with a different time-index, nor that consequentialism would be the foundational type of epistemic justification for the scientists (Stuart, 2022a).

4.4 Tools of the imagination

Some philosophers have recently begun discussing scientific tools as things which encode knowledge in themselves (Baird 2004) or which assist scientists in reasoning about one system by means of another (Carrillo and Knuuttila 2021; de Oliveira 2022; Knuuttila 2011; 2021). While it is clear in general that scientists use tools to extend the power of their hands and minds, there are also tools that extend the power of the imagination. More specifically, if a tool is something that provides impetus, direction, or focus to an action, then certainly thought experiments, computer simulations, models, visualizations, and metaphors can be thought of as tools that direct and focus the scientific imagination in useful ways (Stuart, 2022b). Not all of these is always a tool of the imagination, and many other things not listed (like formal languages, analogies, and jokes) could count as tools of imagination. In any case, one important question is, for any given tool of the imagination, how is it best designed and evaluated?

Adopting the tripartite framework described in the previous section, we can identify tools whose consequences on given acts of imagination are known with relative certainty (because they were used in the past and we know what their effects were), tools whose consequences on given acts of imagination are not known but can be guessed with some confidence (these are tools that are recommended today for use on problems whose solutions are not known), and tools whose consequences on given acts of imagination are not known and cannot be guessed (these are tools that might be used to train the next generation of scientists, but which may or may not be helpful in solving any specific problem). In the first scenario, a straightforward evaluation of consequences is possible, and this is what scientists do. In the second scenario, certain tools are recommended for use because scientists feel they can safely assume that those tools will guide the imagination in a fruitful direction, though they cannot know for certain whether their application will yield positive results in any particular case without having already tried it. In the third scenario, certain tools are recommended for use because scientists feel they will be helpful for future scientists in general, but as training exercises for the imagination rather than as particular problem-solving tools (Stuart, 2022b).

4.5 Varia

It was noted that there are two opposite reactions scientists can have in response to discussions about imagination. These stem from the fact that imagination is not an "official" component of the scientific method. This means that scientists do not have shared standards for when it is used, or how to use it, or teach it. This makes scientific imagination an exciting and wide-open area to research. However, interestingly, this lack of standardization either frustrates or excites scientists. Some want standards for each part of their work. But when it comes to imagination, they find none, and this generates feelings of frustration. A similar issue arises, not with standardization, but with transparency. Scientists tend to believe that each step in their method should be available to inspection, calibration, and verification. The workings of imagination are not transparent. Try though they might, they cannot say for certain what is happening when they imagine. This is another source of epistemic agony. On the other hand, there is a certain subset of participants, typically those with backgrounds or interest in art or the humanities, who believe that this mysterious lawlessness of the imagination is something to be celebrated, something that makes science exciting and human and worth doing.

5. Roads not yet travelled

There are many questions, both new and old, that remain to be answered. I will briefly hint at some of these here.

The first set of issues concerns the nature of scientific imagination. There are several taxonomies of kinds of imagination we might look to (Currie and Ravenscroft 2002; Strawson 1971; Stevenson 2003; Walton 1990; Stuart 2019b; Van Leeuwen 2013; 2014), and one that specifically concerns scientific imagination (Salis and Frigg 2020). But these are almost entirely based on anecdotal or introspective evidence. Qualitative methods are capable of bringing different notions of scientific imagination to light. It could profit the study of imagination greatly to develop a taxonomic map of scientific imagination, which displayed where to find the different kinds of scientific imagination in science, what the different kinds of imagination are used for, and how they are related to one another. The end goal would be to combine this with similar maps for non-scientific disciplines, for example, imagination in art, humanities, law, business, and so on. Such an achievement would go a long way toward capturing just what imagination really is.

A necessary step along the way would be to consider the relations between imagination and similar cognitive processes that have been discussed in philosophy, e.g., supposition, conception, and creativity (Balcerak Jackson, 2016; Arcangeli, 2017a; Sánchez-Dorado, 2020; Stokes, 2014). For example, supposition, on some accounts, is “colder” than imagination. That is, some claim that it is easy to suppose that something horrible happened for the sake of argument, while it is painful or repulsive to imagine the same thing. On some accounts, supposition is completely different from imagination, and for others, supposition is a kind of imagination. Do scientists also differentiate between these processes? Do they employ them both, and if so, are there differences in the contexts in which they are deployed, and if so, why? Further, for some scientists, imagination seems to be co-extensive with creativity. But is creativity also co-extensive with supposition? Qualitative methods might not force philosophers to (re)define their terms in particular ways, but it can productively inform the discussion.

The second set of issues concerns various way of extending our focus beyond the individual. Social epistemology is a field of philosophy that starts by questioning epistemology’s exclusive focus on the epistemic state of the individual, and insists instead on the value of considering how *groups* and members of groups gain knowledge (for a recent overview, see O’Connor, Goldberg, and Goldman 2023). Some main topics of focus within this movement have been whether groups themselves can have beliefs that none of the members have, whether they can have a special kind of knowledge or justification, and how groups might best be arranged to promote the achievement of epistemic ends. The idea would be to adopt this framework and apply it to scientific imagination, perhaps as a way to criticize, complexify, or support existing ideas in that literature, or simply to gain a better grasp of the social aspect of scientific imagination. In a similar vein, there are literatures on “extended” and “distributed” cognition, which argue that epistemology should not stop at the end of the brainstem, or even at the body, but also focus on the tools we use to think (see, e.g., Clark and Chalmers 1998; and Menary 2007 for extended cognition, Hutchins, 1996, for extended cognition). Again, the focus on this literature has traditionally not been on imagination, but attempting to transfer these frameworks and their insights could certainly be fruitful.

Scientists sometimes imagine individually, for example, on their own while waiting for a breakthrough. But based on the empirical data collected in Study 1 and 2, the work of the imagination was often most productive in group settings, and in combination with external representation devices (computers, white boards, pen and paper, etc.). This suggests a social and distributed view of imagination.

The distribution and extension of imagination from the individual to the greater laboratory context makes sense, and is consistent with Nersessian’s analytic orientation towards cognitive ethnography that she calls distributed cognition, according to which cognition in science should be analyzed at the level of the entire laboratory, in terms of individual and group cognition but also with a focus on representational tools (both inside and outside the mind) (see, e.g., Nersessian 2022, especially chapters 1 and 2). This framework could helpfully explain how scientists supercharge their imaginations by running them in parallel with others, and with their devices. Much more can and should be said about how this works.

Two wrinkles are interesting to note here. Scientists say that certain kinds of problems were best addressed using imagination by oneself, while others were better addressed in group settings (Stuart, 2019c). Why might this be? Perhaps the kinds of questions best addressed alone were those where the scientist is confident that they only need a little imagination to solve, and therefore external help isn't necessary. Or perhaps it is the nature of certain problems that collaboration confuses or distracts. More research is necessary here. Second, scientists claimed that their most imaginative moments came neither alone nor in the lab, but at conferences, in the times between talks while discussing in small groups. They claimed this often happened when the talks they attended had little or nothing to do with their own research. It's possible that this could be explained simply by appeal to the general truism that exposure to different ideas, methods, and frameworks can "open the mind" to new possibilities. Or it could be that listening to irrelevant talks gives the scientist just enough distraction to activate what is sometimes called the "shower" principle: roughly, that our conscious mind sets up a question and the unconscious mind suggests answers, but only when distracted to the right degree. But again, it would be interesting to explore this phenomenon further. For example, does the inspirational power of such group discussions depend on the "distance" between the topic or content of the talk and the research area of the scientist and discussion-mates? If so, what is the ideal "distance"? Does this kind of inspiration tend to happen at specific junctures in the trajectory of problem-solving, and if so, which, and why?

A third set of issues emerges when trying to apply findings about imagination in non-scientists to the study of scientific imagination. We said above that some extensions can be made with confidence, though the details will require further work. For example, one interesting discovery already mentioned is the aphantasia-hyperphantasia spectrum. Surely, some scientists will be aphantasics, that is, they will not be able to voluntarily call to mind sensory content. But how many scientists are aphantasics, and how does it affect their work, and the way imagination is used in group settings? In an interview with a mathematician, I was told that there is split in mathematical imagination styles that cleaves the discipline in two: Half of all mathematicians explore questions in a visual way, while the other half employ non-visual, conceptual thinking. This creates difficulty for both sides. Is it possible that the non-sensory half of mathematicians experience some form of aphantasia? That would be surprising, as the general prevalence of aphantasia in humans is currently thought to be only 2-3% (Faw, 2009; Zeman et al., 2020). However, recent work employing quantitative methods suggests that 16% (of a small sample of biologists) described themselves as fully aphantasic, and 35% as aphantasic to some degree (McLoone et al., 2023). This raises the general question of the prevalence of aphantasia among scientists, and across disciplines. It would be very interesting to know why certain disciplines have more aphantasics than others, if they do, and how the content or methods of those disciplines explains or is predicted by that prevalence.

Another phenomenon found in non-scientists that can be assumed to exist in science is called "imaginative resistance." This is the felt inability to imagine certain things. Several competing accounts of the phenomenon exist. For example, perhaps people cannot imagine something because they cannot find a way to make sense of it, or because it contains a hidden contradiction, or because it is very unusual, or because they find it morally distasteful and fear it will "contaminate" them (see, e.g., Weatherson, 2004; Kim, Kneer & Stuart, 2018; Black & Barnes, 2020; Barnes & Black, 2016; Stueber, 2011; Liao, 2016; Liao, et al., 2014; Gendler, 2000). So far there is very little research on this phenomenon in science (though see Savojardo, 2022). It would be very interesting to perform a qualitative study about when and why imaginative resistance occurs in science, if it does. Savojardo considers the possibility of situations in which previous background assumptions clash with new hypotheses, thus generating imaginative resistance. This is certainly an interesting place to start looking for the phenomenon.

A fourth set of issues concerns the downstream ethical consequences of imagination's use and distribution in science. For instance, lack of ethical foresight might be best characterized in terms of a lack of moral imagination. In a recent book called *Science and the Moral Imagination*, Matthew Brown (2020) claims exactly this, that scientists and engineers ought to investigate the ethics of their practice carefully, and that exercising their moral imagination is key. Qualitative methods could be very useful in analyzing how the moral imagination of scientists are currently trained, evaluated, and conceived in science, to extract further norms for its use, and provide additional recommendations for best practices.

There is also an important unanswered question about the epistemology of scientific imagination. Above we saw that scientists are very concerned with the consequences of their imaginings. But what makes a consequence epistemically good? One family of options is to characterize consequences in terms of mental states. Thus, an imagining is good for an individual scientist if, other things being equal, it increases the number of true beliefs that individual has. Or perhaps we want to increase the amount of *knowledge* the individual has. Or *understanding*. Another possibility is to consider the consequences of imaginings for *groups* of scientists. Perhaps groups cannot have mental states like beliefs, but it seems possible to evaluate the consequences of imaginings as good or bad for the collective. A third family of options would be to understand good consequences not in terms of epistemic states (like true belief or knowledge), but in terms of scientific problem-solving abilities. Thus, an imagining can open up new ways of solving particular problems, and they can be good in that sense, even if they do not produce new true beliefs. This is an open question, and a very important one in current discussions of the epistemology of science. Qualitative data on this question is sorely needed.

A final set of issues concerns the pursuit of other analytic frameworks for investigating scientific imagination. For example, the above-mentioned studies mostly focused on imagination as something done primarily with the mind, not the body. But embodied accounts of cognition suggest that this only tells part of the story (Clavel Vázquez & Clavel-Vázquez, 2023; Rucińska & Gallagher, 2021). Qualitative studies focusing specifically on the embodied component of imagination would be very interesting. A still different analytic framework would be one inspired by the growing corpus of work on the *logic* of imagination (see, e.g., Berto, 2017; 2022; Canavotto et al., 2020; Casas-Roma et al.,, 2019). Specifically, it would be illuminating to see which valid or cogent reasoning schemas could be extracted from the imaginative reasoning processes of scientists, and representing these logically. Doing so would open up new possibilities for normative accounts of scientific imagination, as well as for encoding imagination in computers. Finally, a more techno-centric framework could be employed. This might focus on computational methods as replacing certain imaginative tasks (Chandrasekharan et al., 2013; Shinod, 2021; Stuart, 2019a). For example, there are already algorithms responsible for designing, performing, and interpreting experiments (Stuart, 2023), which are traditionally thought of (at least partially) as acts of imagination. How will the introduction of artificial intelligence and big data change scientific imagination? This is something to keep an eye on.

6. Conclusion

Science is an extremely complex set of practices. Qualitative approaches celebrate complexity, and this gives them an advantage when it comes to understanding what science is, how it is done, why it succeeds, and how it can be improved.

Cognitive ethnographic methods have now yielded insights into the nature and function of scientific imagination, which could not have been found otherwise. This may be considered as a proof of concept, not for cognitive ethnography, which is already well-motivated, but for the application of cognitive ethnographic methods to specific cognitive processes like imagination in science.

In particular, this paper has presented some early findings on scientific imagination that profited from the use of qualitative methods, including that imagination is valued for its problem-solving power, and that it is approved for use only in attempting to solve maximally specific problems for which the usual methods have already failed to solve. We saw that different scientists have different views about the importance of imagination for science in general, and about the strengths of their own imaginations, and these attitudes varied in a consistent way: scientists who were earlier in their careers or members of traditionally underrepresented groups tended to avoid imagination and focus on more traditionally valued scientific abilities, often outsourcing work that requires imagination to others. There are important negative ethical and epistemic effects of this situation. Finally, we also saw that while scientists sometimes employ evaluative frameworks such as deontic or virtue theoretic epistemology, they seem to be best described as epistemological consequentialists when it comes to the imagination, and the tools that empower imagination.

We closed with six sets of open issues, concerning (i) the nature of scientific imagination, (ii) social and embodied imagination, (iii) so-called “imaginative resistance” in science, (iv) other downstream ethical consequences of how imagination is organized and used in science, (v) further explorations of what grounds consequentialist evaluations of imagination, and (vi) other possible lenses through which to perform qualitative research on scientific imagination.

All the arguments in this paper would likely also motivate using qualitative methods to study other cognitive-cultural processes and properties, including creativity, beauty, humor, and emotion in science. We have much to look forward to as the use of qualitative methods in the study of science increases.

References

Adam Bulley. 2018. "The History and Future of Human Prospection." *Evolutionary Studies in Imaginative Culture* 2 (1): 75. https://doi.org/10.26613/esic.2.1.75.

Ankeny, Rachel A., Heather J. Bray, and Emily A. Buddle. 2022. "Values of Australian Meat Consumers Related to Sheep and Beef Cattle Welfare: What Makes a Good Life and a Good Death?" *Food Ethics* 8 (1): 1–17. https://doi.org/10.1007/s41055-022-00114-2.

Arcangeli, Margherita. 2010. "Imagination in Thought Experimentation: Sketching a Cognitive Approach to Thought Experiments." In *Model-Based Reasoning in Science and Technology: Abduction, Logic, and Computational Discovery*, edited by Lorenzo Magnani, Walter Carnielli, and Claudio Pizzi, 571–87. Studies in Computational Intelligence. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-15223-8_32.

———. 2017a. *Supposition and the Imaginative Realm: A Philosophical Inquiry*. London: Routledge. https://www.routledge.com/Supposition-and-the-Imaginative-Realm-A-Philosophical-Inquiry/Arcangeli/p/book/9781138223042.

———. 2017b. "Thought Experiments in Model-Based Reasoning." In *Springer Handbook of Model-Based Science*, edited by Lorenzo Magnani and Tommaso Bertolotti, 463–93. Springer Handbooks. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-30526-4_21.

———. 2018. "The Hidden Links between Real, Thought and Numerical Experiments." *Croatian Journal of Philosophy* 18 (52): 3–22.

Arditi, Aries, Jeffery D. Holtzman, and Stephen M. Kosslyn. 1988. "Mental Imagery and Sensory Experience in Congenital Blindness." *Neuropyschologia* 26: 1–12.

Baird, Davis. 2004. *Thing Knowledge: A Philosophy of Scientific Instruments*. Berkeley: University of California Press.

Balcerak Jackson, Magdalena. 2016. "On the Epistemic Value of Imagining, Supposing, and Conceiving." In *Knowledge Through Imagination*, edited by Amy Kind and Peter Kun. Oxford: Oxford University Press.

Barnes, Jennifer, and Jessica Black. 2016. "Impossible or Improbable: The Difficulty of Imagining Morally Deviant Worlds." *Imagination, Cognition and Personality* 36 (1): 27–40. https://doi.org/10.1177/0276236616643268.

Bascandziev, Igor, and Paul L. Harris. 2020. "Can Children Benefit from Thought Experiments?" In *The Scientific Imagination*, edited by Arnon Levy and Peter Godfrey-Smith, 262–79. Oxford University Press. https://oxford.universitypressscholarship.com/view/10.1093/oso/9780190212308.001.0001/oso-9780190212308-chapter-12.

Berg, Jeffrey J., Adrian W. Gilmore, Ruth A. Shaffer, and Kathleen B. McDermott. 2021. "The Stability of Visual Perspective and Vividness during Mental Time Travel." *Consciousness and Cognition* 92 (July): 103116. https://doi.org/10.1016/j.concog.2021.103116.

Berto, Francesco. 2017. "Impossible Worlds and the Logic of Imagination." *Erkenntnis* 82 (6): 1277–97. https://doi.org/10.1007/s10670-017-9875-5.

———. 2022. *Topics of Thought: The Logic of Knowledge, Belief, Imagination*. 1st ed. Oxford University PressOxford. https://doi.org/10.1093/oso/9780192857491.001.0001.

Black, Jessica E., and Jennifer L. Barnes. 2020. “Morality and the Imagination: Real-World Moral Beliefs Interfere with Imagining Fictional Content.” *Philosophical Psychology* 33 (7): 1018–44. https://doi.org/10.1080/09515089.2020.1775799.

Blomkvist, Andrea. 2023. “Aphantasia: In Search of a Theory.” *Mind & Language* 38 (3): 866–88. https://doi.org/10.1111/mila.12432.

Buddle, Emily A., Heather J. Bray, and Rachel A. Ankeny. 2021. “‘Of Course We Care!’: A Qualitative Exploration of Australian Livestock Producers’ Understandings of Farm Animal Welfare Issues.” *Journal of Rural Studies* 83 (April): 50–59. https://doi.org/10.1016/j.jrurstud.2021.02.024.

Byrne, Ruth M.J. 2005. *The Rational Imagination: How People Create Alternatives to Reality*. Cambridge: MIT Press.

Canavotto, Ilaria, Francesco Berto, and Alessandro Giordani. 2020. “Voluntary Imagination: A Fine-Grained Analysis.” *The Review of Symbolic Logic*, 1–26. https://doi.org/10.1017/S1755020320000039.

Carrillo, Natalia, and Tarja Knuuttila. 2021. “An Artifactual Perspective on Idealization: Constant Capacitance and the Hodgkin and Huxley Model.” In *Models and Idealizations in Science: Artifactual and Fictional Approaches*, edited by Alejandro Cassini and Juan Redmond, 51–70. Logic, Epistemology, and the Unity of Science. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-65802-1_2.

Casas-Roma, Joan, Antonia Huertas, and M. Elena Rodríguez. 2019. “The Logic of Imagination Acts: A Formal System for the Dynamics of Imaginary Worlds.” *Erkenntnis*, June. https://doi.org/10.1007/s10670-019-00136-z.

Chandrasekharan, Sanjay, Nancy Nersessian, and Vrishali Subramanian. 2013. *Computational Modeling: Is This the End of Thought Experiments in Science?* Edited by Mélanie Frappier.

Clark, Andy, and David J. Chalmers. 1998. “The Extended Mind.” *Analysis* 58: 7–19.

Clavel Vázquez, María Jimena, and Adriana Clavel-Vázquez. 2023. “Robustly Embodied Imagination and the Limits of Perspective-Taking.” *Philosophical Studies* 180 (4): 1395–1420. https://doi.org/10.1007/s11098-023-01936-4.

Cowan, Nelson. 2001. “The Magical Number 4 in Short-Term Memory: A Reconsideration of Mental Storage Capacity.” *Behavioral and Brain Sciences* 24 (1): 87–114. https://doi.org/10.1017/S0140525X01003922.

Currie, Gregory, and Ian Ravenscroft. 2002. *Recreative Minds: Imagination in Philosophy and Psychology*. Clarendon Press.

Dawes, Alexei J., Rebecca Keogh, Thomas Andrillon, and Joel Pearson. 2020. “A Cognitive Profile of Multi-Sensory Imagery, Memory and Dreaming in Aphantasia.” *Scientific Reports* 10 (1): 10022. https://doi.org/10.1038/s41598-020-65705-7.

Dennett, Daniel C. 1981. “The Nature of Images and the Introspective Trap.” In *Readings in Philosophy of Psychology, Volume II*, edited by Ned Block, 128–34. Harvard University Press. https://doi.org/10.4159/harvard.9780674594722.c10.

Dunbar, Kevin. 1995. “How Scientists Really Reason: Scientific Reasoning in Real-World Laboratories.” In *Mechanisms of Insight*. Cambridge, MA: MIT Press.

Faw, Bill. 2009. “Conflicting Intuitions May Be Based On Differing Abilities: Evidence from Mental Imaging Research.” *Journal of Consciousness Studies* 16 (January): 45–68.

Feyerabend, Paul. 1975. *Against Method: Outline of an Anarchistic Theory of Knowledge*. London; New York: Verso.

French, Steven. 2020. "Imagination in Scientific Practice." *European Journal for Philosophy of Science* 10 (3): 27. https://doi.org/10.1007/s13194-020-00291-z.
Frigg, Roman. 2010. "Models and Fiction." *Synthese* 172 (2): 251–68.
Gendler, Tamar Szabó. 2000. "The Puzzle of Imaginative Resistance." *The Journal of Philosophy* 97 (2): 55–81. https://doi.org/10.2307/2678446.
Gopnik, Alison. 1996. "The Scientist as Child." *Philosophy of Science* 63 (4): 485–514.
Hadamard, Jacques. 1945. *The Mathematician's Mind: The Psychology of Invention in the Mathematical Field*. Princeton: Princeton University Press.
Holton, Gerald. 1978. *The Scientific Imagination — Gerald Holton*. Cambridge, MA: Harvard University Press. https://www.hup.harvard.edu/catalog.php?isbn=9780674794887.
———. 1996. "On the Art of the Scientific Imagination." *Daedalus* 125: 183–208.
Hutchins, Edwin. 1996. *Cognition in the Wild*. Cambridge, MA: MIT Press. https://mitpress.mit.edu/9780262581462/cognition-in-the-wild/.
Ivanova, Milena, Bridget Ritz, Marcela Duque, and Brandon Vaidyanathan. 2023. "Beauty in Experiment: A Qualitative Analysis of Aesthetic Experiences in Scientific Practice." https://philsci-archive.pitt.edu/22546/.
Jacob, Francis. 2001. "Imagination in Art and Science." *Kenyon Review* 23: 113–21.
Jasanoff, Sheila, and Sang-Hyun Kim. 2009. "Containing the Atom: Sociotechnical Imaginaries and Nuclear Power in the United States and South Korea." *Minerva* 47 (2): 119. https://doi.org/10.1007/s11024-009-9124-4.
Jensvold, M. L. A., and R. S. Fouts. 1993. "Imaginary Play in Chimpanzees (Pan Troglodytes)." *Human Evolution* 8 (3): 217–27. https://doi.org/10.1007/BF02436716.
Kim, Hanna, Markus Kneer, and Michael T. Stuart. 2018. "The Content-Dependence of Imaginative Resistance." In *Advances in Experimental Philosophy of Aesthetics*, edited by Florian Cova and Sébastien Réhault, 143–66. London: Bloomsbury.
Kind, Amy. 2018. "How'd Imagination Become So Hot?" *The Junkyard* (blog). May 9, 2018. https://junkyardofthemind.com/blog/2018/5/8/howd-imagination-become-so-hot.
Kind, Amy, and Peter Kung, eds. 2016. *Knowledge Through Imagination*. Oxford, New York: Oxford University Press.
Klein, Stanley B. 2013. "The Complex Act of Projecting Oneself into the Future." *Wiley Interdisciplinary Reviews. Cognitive Science* 4 (1): 63–79. https://doi.org/10.1002/wcs.1210.
Knuuttila, Tarja. 2011. "Modelling and Representing: An Artefactual Approach to Model-Based Representation." *Studies in History and Philosophy of Science Part A* 42 (2): 262–71. https://doi.org/10.1016/j.shpsa.2010.11.034.
———. 2021. "Epistemic Artifacts and the Modal Dimension of Modeling." *European Journal for Philosophy of Science* 11 (3): 65. https://doi.org/10.1007/s13194-021-00374-5.
Kosslyn, Stephen, William L. Thompson, and Giorgio Ganis. 2006. *The Case for Mental Imagery*. Oxford: Oxford University Press.
Leonelli, Sabina. 2008. "Performing Abstraction: Two Ways of Modelling Arabidopsis Thaliana." *Biology and Philosophy* 23 (January): 509–28. https://doi.org/10.1007/s10539-007-9081-y.
———. 2016. *Data-Centric Biology: A Philosophical Study*. Chicago, IL: University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/D/bo24957334.html.
Levy, Arnon, and Peter Godfrey-Smith, eds. 2019. *The Scientific Imagination*. Oxford, New York: Oxford University Press.

Liao, Shen-yi. 2016. “Imaginative Resistance, Narrative Engagement, Genre.” *Res Philosophica* 93 (2): 461–82. https://doi.org/10.11612/resphil.2016.2.93.3.

Liao, Shen-yi, Nina Strohminger, and Chandra Sekhar Sripada. 2014. “Empirically Investigating Imaginative Resistance.” *British Journal of Aesthetics* 54 (3): 339–55. https://doi.org/10.1093/aesthj/ayu027.

Liu, Jianghao, Minye Zhan, Dounia Hajhajate, Alfredo Spagna, Stanislas Dehaene, Laurent Cohen, and Paolo Bartolomeo. 2023. “Visual Mental Imagery in Typical Imagers and in Aphantasia: A Millimeter-Scale 7-T fMRI Study.” bioRxiv. https://doi.org/10.1101/2023.06.14.544909.

Lombrozo, Tania. 2020. “‘Learning by Thinking’ in Science and in Everyday Life.” In *The Scientific Imagination*, edited by Arnon Levy and Peter Godfrey-Smith, 230–49. Oxford University Press. https://oxford.universitypressscholarship.com/view/10.1093/oso/9780190212308.001.0001/oso-9780190212308-chapter-10.

Mandel, David, Denis Hilton, and Patrizia Catellani. 2005. *The Psychology of Counterfactual Thinking*. New York: Routledge.

Matsuzawa, Tetsuro. 2020. “Pretense in Chimpanzees.” *Primates* 61 (4): 543–55. https://doi.org/10.1007/s10329-020-00836-z.

McAllister, James. W. 2012. “Thought Experiment and the Exercise of Imagination in Science.” In *Thought Experiments in Science, Philosophy, and the Arts*. Routledge.

McLoone, Brian, Cassandra Grützner, and Michael T. Stuart. 2023. “Counterpossibles in Science: An Experimental Study.” *Synthese* 201 (1): 27. https://doi.org/10.1007/s11229-022-04014-0.

McNeil, Maureen, Michael Arribas-Ayllon, Joan Haran, Adrian Mackenzie, and Richard Tutton. 2017. “Conceptualizing Imaginaries of Science, Technology, and Society.” In *The Handbook of Science and Technology Studies*, edited by Ulrike Felt, Rayvon Fouche, Clark A. Miller, and Laurel Smith-Doerr, 435. Cambridge, MA: MIT Press.

Menary, Richard. 2007. *Cognitive Integration*. London: Palgrave Macmillan UK. https://doi.org/10.1057/9780230592889.

Meynell, Letitia. 2014. “Imagination and Insight: A New Account of the Content of Thought Experiments.” *Synthese* 191 (17): 4149–68. https://doi.org/10.1007/s11229-014-0519-x.

———. 2018. “Images and Imagination in Thought Experiments.” In *The Routledge Companion to Thought Experiments*. Routledge. https://doi.org/10.4324/9781315175027.ch28.

Mills, C. Wright. 1959. *The Sociological Imagination*. Oxford, New York: Oxford University Press.

Mitchell, Robert W., ed. 2002. *Pretending and Imagination in Animals and Children*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511542282.

Mitroff, Ian I. 1974. *The Subjective Side of Science: A Philosophical Inquiry into the Psychology of the Apollo Moon Scientists*. Amsterdam: Elsevier.

Murphy, Alice. 2020. “Toward a Pluralist Account of the Imagination in Science.” *Philosophy of Science* 87 (5): 957–67. https://doi.org/10.1086/710620.

Nersessian, Nancy J. 1992. “How Do Scientists Think? Capturing the Dynamics of Conceptual Change in Science.” In *Cognitive Models of Science*, edited by Ronald N. Giere, 3–44. Minneapolis: University of Minnesota Press.

———. 2008. *Creating Scientific Concepts*. Cambridge: MIT Press.

———. 2022. *Interdisciplinarity in the Making: Models and Methods in Frontier Science*. Cambridge, MA: MIT Press. https://doi.org/10.7551/mitpress/14667.001.0001.

Nersessian, Nancy J., and Miles MacLeod. 2022. "Rethinking Ethnography for Philosophy of Science." *Philosophy of Science* 89 (4): 721–41. https://doi.org/10.1017/psa.2022.8.

O'Connor, Cailin, Sanford Goldberg, and Alvin Goldman. 2023. "Social Epistemology." In *The Stanford Encyclopedia of Philosophy*, edited by Edward N. Zalta and Uri Nodelman, Winter 2023. Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/win2023/entries/epistemology-social/.

Oliveira, Guilherme Sanches de de. 2022. "Radical Artifactualism." *European Journal for Philosophy of Science* 12 (2): 1–33. https://doi.org/10.1007/s13194-022-00462-0.

Osbeck, Lisa M., and Stephen L. Antczak. 2021. "Generalizability and Qualitative Research: A New Look at an Ongoing Controversy." *Qualitative Psychology* 8 (1): 62–68. https://doi.org/10.1037/qup0000194.

Özdemir, Ömer Faruk. 2009. "Avoidance from Thought Experiments: Fear of Misconception." *International Journal of Science Education* 31: 1–20.

Pylyshyn, Zenon W. 2002. "Mental Imagery: In Search of a Theory." *Behavioral and Brain Sciences* 25: 157–82.

Ribot, Théodule. 1906. *Essay on the Creative Imagination*. Translated by Albert H. N. Baron. London: Open Court. https://www.gutenberg.org/ebooks/26430/pg26430-images.html.utf8.

Ritson, Sophie. 2021. "Creativity and Modelling the Measurement Process of the Higgs Self-Coupling at the LHC and HL-LHC." *Synthese* 199 (5): 11887–911. https://doi.org/10.1007/s11229-021-03317-y.

Rocke, Alan J. 2010. *Image and Reality: Kekulé, Kopp, and the Scientific Imagination*. Synthesis. Chicago ; London: The University of Chicago Press.

Rucińska, Zuzanna, and Shaun Gallagher. 2021. "Making Imagination Even More Embodied: Imagination, Constraint and Epistemic Relevance." *Synthese* 199 (3): 8143–70. https://doi.org/10.1007/s11229-021-03156-x.

Salis, Fiora. 2020. "Learning through the Scientific Imagination." *Argumenta - Journal of Analytic Philosophy* 6 (1): 65–80.

———. 2021. "The New Fiction View of Models." *The British Journal for the Philosophy of Science* 72 (3): 717–42. https://doi.org/10.1093/bjps/axz015.

Salis, Fiora, and Roman Frigg. 2020. "Capturing the Scientific Imagination." In *The Scientific Imagination*, edited by Arnon Levy and Peter Godfrey-Smith, 17–50. Oxford University Press. https://oxford.universitypressscholarship.com/view/10.1093/oso/9780190212308.001.0001/oso-9780190212308-chapter-2.

Sánchez-Dorado, Julia. 2020. "Novel & Worthy: Creativity as a Thick Epistemic Concept." *European Journal for Philosophy of Science* 10 (3): 1–23. https://doi.org/10.1007/s13194-020-00303-y.

Savage-Rumbaugh, Sue, and Kelly McDonald. 1988. "Deception and Social Manipulation in Symbol-Using Apes." In *Machiavellian Intelligence: Social Expertise and the Evolution of Intellect in Monkeys, Apes, and Humans*, 224–37. New York, NY, US: Clarendon Press/Oxford University Press.

Savojardo, Valentina. 2022. "Imaginative Resistance in Science." *Foundations of Science*, July. https://doi.org/10.1007/s10699-022-09857-x.

Shinod, N. K. 2021. "Why Computer Simulation Cannot Be an End of Thought Experimentation." *Journal for General Philosophy of Science* 52 (3): 431–53. https://doi.org/10.1007/s10838-020-09546-y.

Sismondo, Sergio. 2020. "Sociotechnical Imaginaries: An Accidental Themed Issue." *Social Studies of Science* 50 (4): 505–7. https://doi.org/10.1177/0306312720944753.

Skolnick Weisberg, Deena. 2020. "Is Imagination Constrained Enough for Science?" In *The Scientific Imagination*, edited by Arnon Levy and Peter Godfrey-Smith, 250–61. Oxford University Press. https://oxford.universitypressscholarship.com/view/10.1093/oso/9780190212308.001.0001/oso-9780190212308-chapter-11.

Stevenson, Leslie. 2003. "Twelve Conceptions of Imagination." *The British Journal of Aesthetics* 43 (3): 238–59. https://doi.org/10.1093/bjaesthetics/43.3.238.

Stokes, Dustin. 2014. "The Role of Imagination in Creativity." In *The Philosophy of Creativity: New Essays*, edited by Elliot Samuel Paul and Scott Barry Kaufman, 157–84. Oxford: Oxford University Press.

Strawson, P. F. 1971. "Imagination and Perception." In *Experience and Theory. Edited by Foster and Swanson.*, 31–54. Amherst, Mass., and London: University of Massachusetts Press and Duckworth.

Stuart, Michael T. 2017. "Imagination: A Sine Qua Non of Science." *Croatian Journal of Philosophy* XVII (49): 9–32.

———. 2019a. "The Role of Imagination in Social Scientific Discovery: Why Machine Discoverers Will Need Imagination Algorithms." In *Scientific Discovery in the Social Sciences*, edited by Mark Addis, Peter C. R. Lane, Peter D. Sozou, and Fernand Gobet, 49–66. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-23769-1_4.

———. 2019b. "Towards a Dual Process Epistemology of Imagination." *Synthese*. https://doi.org/10.1007/s11229-019-02116-w.

———. 2019c. "Everyday Scientific Imagination: A Qualitative Study of the Uses, Norms, and Pedagogy of Imagination in Science." *Science & Education* 28 (6–7): 711–30. https://doi.org/10.1007/s11191-019-00067-9.

———. 2020. "The Productive Anarchy of Scientific Imagination." *Philosophy of Science* 87 (5): 968–78. https://doi.org/10.1086/710629.

———. 2022a. "Scientists Are Epistemic Consequentialists about Imagination." *Philosophy of Science* 90 (3): 518–38. https://doi.org/10.1017/psa.2022.31.

———. 2022b. "Sharpening the Tools of Imagination." *Synthese* 200 (6): 451. https://doi.org/10.1007/s11229-022-03939-w.

———. 2023. "The Future Won't Be Pretty: The Nature and Value of Ugly, AI-Designed Experiments." In *The Aesthetics of Scientific Experiments*. Routledge.

Stuart, Michael T., and Hannah Sargeant. forthcominga. "Inclusivity in the Education of Scientific Imagination." In *Building Inclusive Ethical Cultures in STEM*, edited by E. Hildt, K. Laas, C. Miller, and E. Brey. London: Routledge.

———. forthcomingb. "The Role of Imagination in Making Water from Moon Rocks: How Scientists Break Constraints on Imagination." *Analysis*.

Stueber, Karsten R. 2011. "Imagination, Empathy, and Moral Deliberation: The Case of Imaginative Resistance." *The Southern Journal of Philosophy* 49 (s1): 156–80. https://doi.org/10.1111/j.2041-6962.2011.00065.x.

Suddendorf, Thomas. 2010. “Episodic Memory versus Episodic Foresight: Similarities and Differences.” *WIREs Cognitive Science* 1 (1): 99–107. https://doi.org/10.1002/wcs.23.

Suddendorf, Thomas, and M. C. Corballis. 1997. “Mental Time Travel and the Evolution of the Human Mind.” *Genetic, Social, and General Psychology Monographs* 123 (2): 133–67.

Taylor, Alfred Maurice. 1967. *Imagination and the Growth of Science*. Schocken Books.

Toon, Adam. 2012. *Models as Make-Believe: Imagination, Fiction and Scientific Representation*. New Directions in the Philosophy of Science. Palgrave Macmillan UK. https://doi.org/10.1057/9781137292230.

Van Leeuwen, Neil. 2013. “The Meanings of ‘Imagine’ Part I: Constructive Imagination.” *Philosophy Compass* 8 (3): 220–30. https://doi.org/10.1111/j.1747-9991.2012.00508.x.

———. 2014. “The Meanings of ‘Imagine’ Part II: Attitude and Action.” *Philosophy Compass* 9 (11): 791–802. https://doi.org/10.1111/phc3.12141.

Vico, Giambattista. 1730. *The New Science of Giambattista Vico: Unabridged Translation of the Third Edition (1744) with the Addition of “Practic of the New Science.”* Translated by Thomas Goddard Bergin and Max Harold Fisch. Cornell University Press. https://www.jstor.org/stable/10.7591/j.ctt20d89gr.

Vygotsky, Lev Semenovich. 1997. *The Collected Works of L. S. Vygotsky: Problems of the Theory and History of Psychology*. Springer Science & Business Media.

Walton, Kendall L. 1990. *Mimesis as Make-Believe: On the Foundations of the Representational Arts*. Cambridge, MA and London: Harvard University Press.

Weatherson, Brian. 2004. “Morality, Fiction, and Possibility.” *Philosophers’ Imprint* 4: 1–27.

Whiteley, Cecily M. K. 2020. “Aphantasia, Imagination and Dreaming.” *Philosophical Studies*, September. https://doi.org/10.1007/s11098-020-01526-8.

Yan, Karen, and Chuan-Ya Liao. 2023. “A Co-Citation Analysis of Cross-Disciplinarity in the Empirically-Informed Philosophy of Mind.” *Synthese* 201 (5): 159. https://doi.org/10.1007/s11229-023-04146-x.

Zeman, Adam, Michaela Dewar, and Sergio Della Sala. 2015. “Lives without Imagery – Congenital Aphantasia.” *Cortex* 73 (December): 378–80. https://doi.org/10.1016/j.cortex.2015.05.019.

Zeman, Adam, Fraser Milton, Sergio Della Sala, Michaela Dewar, Timothy Frayling, James Gaddum, Andrew Hattersley, et al. 2020. “Phantasia–The Psychological Significance of Lifelong Visual Imagery Vividness Extremes.” *Cortex* 130 (September): 426–40. https://doi.org/10.1016/j.cortex.2020.04.003.