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Imagination in science

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Abstract

While discussions of the imagination have been limited in philosophy of science, this is beginning to change. In recent years, a vast literature on imagination in science has emerged. This paper surveys the current field, including the changing attitudes towards the scientific imagination, the fiction view of models, how the imagination can lead to knowledge and understanding, and the value of different types of imagination. It ends with a discussion of the gaps in the current literature, indicating avenues for future research.

1 | INTRODUCTION

Discussions of the imagination have been limited in philosophy of science. Why might this be the case? One reason is that we typically associate the imagination with creativity and the arts, practices that we often regard as standing in sharp contrast with science. We can imagine things that we know are not true whether in the context of our engagement with fictions such as novels and films, when we fantasise or daydream, or when we play games of make-believe as children. Furthermore, we celebrate artists and their abilities to richly conjure up new worlds and ideas. The imagination as characterised in this sense is part of why we value our imagination, and the imaginations of others, so highly.[1] We can note that 'creative' is often used interchangeably with 'imaginative'. This connection can be traced back to Kant who took creative genius to be an imaginative activity 'for which no determinate rule can be given' (1781/2000, p. 186).

The issue of what creativity consists in is disputed but many have accepted the notion that creativity and imagination are closely linked (Gaut, 2003; Stokes, 2016), with some arguing that the imagination is a necessary component of creativity (Hills & Bird, 2018, 2019). While Kant argued that only artists, and not scientists, can fall under the category of creative genius, contemporary accounts of creativity broaden their scope to include scientists. We praise scientists for their innovative uses of imagination that lead to important and often surprising discoveries, and this is reflected in the reward structure of science (Ivanova & French, 2020, p. 5). Take, for example, Friedrich Kekulé's vision of ouroboros, the symbol of a snake holding its own tail in its mouth, which he claimed led him to the idea that the structure of a benzene molecule is ring-shaped. Or Nikola Tesla's description of the creative processes that led to his inventions that involved visualising his constructions and augmenting them in his mind's eye, without the aid of physical drawings of their design (Kind, 2016, p. 154).

There seems to be at least some role for imagination in science, then: the imagination can be crucial in the process of coming up with theories, can lead to interesting lines of research and can contribute to the formation of new technologies. But perhaps the reason why philosophers have been dismissive of the imagination is because it clashes with how we think scientists make epistemic progress.

One way in which this can be articulated is by appealing to the distinction between the context of discovery and the context of justification as introduced by Reichenbach (1938). This distinction separates questions about how new ideas are generated from questions about how the validity of those ideas are assessed. According to those who adopt the distinction, issues surrounding the context of discovery may be interesting for psychological or sociological studies of science, but not for philosophical ones. For example, Popper (1934/2002) argues that justification ought to be bracketed from any references to the mental activities that produced the hypothesis in question as they are not susceptible to logical analysis. As Stokes (2016) points out, Popper dismisses scientific creativity for the opposite reason to Kant. For Kant, the process of scientific discovery can be outlined in a systematic way and can be taught to others and is therefore not genuinely creative. Whereas 'one cannot learn to write inspired poetry' (1781/2000, 187–188) nor can artistic creativity be explained.[2] Yet for Popper, it is because scientific discovery is not subject to such rational analysis that it cannot be the proper subject matter for philosophy. On this view, the imagination may play some role in, say, conjuring up new theories about the world, but this is irrelevant when it comes to assessing their epistemic value.

However, in the second half of the twentieth century, the discovery-justification distinction came under scrutiny. Philosophers emphasised the difficulties in separating the features involved in discovery from those that are involved in justification, claiming that this shows the distinction collapses. Others demonstrated that discovery is not a wholly unconstrained realm, either by attempting to set out a logic of discovery or by showing that it is at least a process that can be subject to analysis (see Schickore, 2018, for an overview). And this can be maintained whilst rejecting the Kantian view as overly simplified. Consequently, scientific discovery becomes a legitimate topic for philosophy.

Furthermore, attitudes towards imagination in science are beginning to change. In recent years, we have seen edited collections dedicated to exploring issues that connect art and science and often make references to the role of fiction and imagination in thought experiments, models, and metaphors in science (Bueno et al., 2018; Frappier et al., 2012; Frigg & Hunter, 2010; Ivanova & French, 2020). Additionally, there is now a volume dedicated purely to investigating the scientific imagination edited by Levy and Godfrey-Smith who, in the introduction to the collection, state how the value of imagination cannot be easily dismissed as limited to the "mere" context of discovery. This is because it plays a role in 'conceiving new theoretical ideas, in exploring the explanatory resources of these ideas, and in working out how to bring theoretical ideas into contact with empirical constraints' (2020, p. 2). There has also been a boom in philosophical studies of the imagination's epistemic uses outside of science, including the ways in which it can aid decision making, contribute to our knowledge of others, and play a part in the acquisition of modal truths (Badura & Kind, 2021; Gendler & Hawthorne, 2002; Kind & Kung, 2016).

2 | FICTION VIEW OF MODELS

The place where the imagination is referenced most often in philosophy of science is in the fiction view of models. Scientists often talk about idealised, simplified models – such as models of the solar system in which the planets are perfectly spherical—as if they were real, concrete systems. How do we make sense of this aspect of scientific practice? A set of views addresses this by comparing models and our engagement with them with fictions in art (Godfrey-Smith, 2006). Traces of such an approach have been present for a long time such as in Vaihinger's philosophy of the "as if" (1911/2004) and more recently in Cartwright's work in which models (including Galilean thought experiments) are compared with fables and parables (1983, 1991, 2010).[3]

A prominent version of the view takes models (and/or thought experiments [Meynell, 2014; Salis & Frigg 2020]) as examples of make-believe, a concept developed by Walton in the context of artistic representations. Make-believe 'is the use of (external) props in imaginative activities' (Walton, 1990, p. 67). Applied to science, the view is that models or thought experiment narratives function as "props" that guide imaginings (Friend, 2020; Frigg, 2010; Levy, 2012; Salis & Frigg 2020; Toon, 2012). The prescriptions to imagine that are licensed by a work of fiction fix the content of the fictional world. Some of what is "true in the fiction" are primary truths, that is, those that are explicitly stated by the text. Other truths are implied and are derived from "principles of generation" such as the Reality Principle which authorises the use of real-world facts to fill in the background of a fiction.

While this set of views have brought about an increased interest in the imagination in science, it is important to note that discussions of the imagination and the fiction view can come apart, and it is not the case that those who defend the role of imagination in science are automatically committed to this view of models or thought experiments. Some who explicitly reject the (Waltonian) fiction account still acknowledge the importance of the imagination in science (French, 2020a; Todd, 2020; Weisberg, 2013). Furthermore, while the imagination is central to make-believe, an important question has been largely neglected: What is meant by the imagination in science? This is especially pertinent given that Walton, at the beginning of *Mimesis and Make Believe*, admits the difficulties with pinning down what the imagination is and what all instances of imagination have in common (1990, 19). By itself, the Waltonian view of models does not necessarily say much about the imagination.

3 | THE NATURE OF IMAGINATION

While explicit discussions of the nature of imagination in science have been mostly missing from the literature, it appears that for many, talk of imagination is automatically linked with visual, mental imagery.[4] In the context of thought experiments, for example, it has been argued that 'the ability to visualise is necessary to most if not all thought experiments' (Gooding 1992), and that thought experiments 'are carried out in the mind and they involve something akin to experience, that is, we typically "see" something happening in a thought experiment' (Brown, 2004, p. 25). Drawing on the example of Stevin's chain, Gendler argues that 'the presence of a mental image may play a crucial cognitive role' Gendler (2004, p. 1154).[5] In the context of models, Levy states that modelling involves a "seeing in the mind's eye" (Levy, 2015, p. 785) and Weisberg takes the fiction view of models to be arguing for the role of "mental pictures" (2013, chapter 4). While some take imagery as a necessary component of imagination (Kind, 2001), it is widely accepted in cognitive science, psychology, and the philosophy of art and mind that the imagination can take various forms. Arcangeli (2010) and Salis and Frigg (2020) use insights from other areas of philosophy to argue that a broader notion of imagination should be employed to better understand its uses in science.

There are many ways in which the imagination has been categorised (Liao and Gendler, 2020), but it is a distinction between the propositional imagination on the one hand, and the non-propositional or "imagistic" imagination on the other, that has prompted recent debates. Propositional imagination consists in imagining *that* something is the case. This kind of imagination is similar to other propositional attitudes such as belief and desire. There is great debate on the relations between this type of imagination and supposition. While terms like "imagine" or "suppose" might be used interchangeably when introducing thought experiments and models, philosophers working on imagination have addressed the connections between the two, given that supposition involves considering hypothetical scenarios. For some, such as Salis and Frigg (2020) and Arcangeli (2018a), supposition is a type of imagining.[6] Others argue for a discontinuity between supposition and imagining, including Balcerak Jackson (2016). Whether or not supposition counts as a form of imagining, it has been differentiated from (other forms of) propositional imagining for various reasons. For example, supposition does not usually bring about affective responses whereas the imagination can. Others claim that supposition is not subject to imaginative resistance. For example, I am able to suppose that a morally deviant world is morally good, but I am unable to imagine this.[7] Finally, supposition is taken to be less constrained than imagination; we can suppose (but not imagine) contradictions (Arcangeli, 2018a; Gendler, 2000; Weinberg & Meskin, 2006).

The propositional imagination differs from the imagistic imagination which is often described as being "perception-like" or having a "quasi-sensory" character. Imagining in this way has a phenomenal quality similar to ordinary perception. The imagistic imagination is not limited to visualisation; we can have imaginings that are correlated with the other senses as well such as auditory or olfactory mental imagery, and there are candidates for other types of mental imagery in science. For example, von Helmholtz's use of thought experiments in *Sensations of Tone* (1875) call upon our auditory imagination.[8] Further, Nersessian (2007, 2018) applies the cognitive science literature on mental models to argue that thought experiments are "embodied representations" and can utilise other perceptual as well as motor representations along with visual mental imagery (2018, p. 319). Gooding (1992) and Hacking (1992) also emphasise the "bodily feel" of thought experiments, arguing that this can contribute to their persuasive force and Toon's Waltonian view of models includes a discussion of embodiment and tactile sensations in the use of physical models (2012, p. 129). This opens the way for an investigation into the embodied imagination in science. However, the focus so far has tended to lie with visual mental imagery.

Salis and Frigg argue that the propositional imagination is both a necessary and sufficient form of imagination in models and thought experiments, and mental imagery is never required. Firstly, they claim that mental imagery is insufficient; models and thought experiments ask us to imagine things like the concept of force or frictionlessness which, they argue, we cannot have perception-like representations of. Instead, they claim, these are best captured as instances of propositional imagination.[9] They also argue that mental imagery is unnecessary; 'it would be implausible to argue that individuals with a poor imagistic ability could not derive the outcome' of say, a Galilean thought experiment (2020, p. 40).

This view has prompted challenges from those advocating a pluralist view of the nature of imagination in science. Murphy (2020b), who focuses on thought experiments, states that when we consider various examples and their role in scientific practice, different thought experiments invite different types of imagination and a philosophical account of imagination in science needs to be able to accommodate this. Mental imagery, Murphy suggests, may be especially useful in cases where understanding is the relevant epistemic output (this is further discussed below), or in instances where we are invited to imagine different perspectives on the same scenario to consider what an observer would see. Others, such as Levy (2020), French (2020b), and Todd (2020), have argued that different types of imagination work together in science. For example, French argues that in Einstein's 1905 paper 'On the Electrodynamics of Moving Bodies', the reader is asked to imagine certain "quasi-sensory" elements such as clocks and rods. These function as "hooks" on which we can hang "belief-like" or propositional features of imagining, that is, we stipulate that the clocks are perfect, and the rods are practically rigid (2020b, p. 8).

Progress is being made when it comes to specifying the nature of imagination in science. But which features determine what kind of imagination is involved in different scientific activities such as theorising, thought experiments and modelling, remains underexplored. Furthermore, it is unclear whether the imagistic imagination can ever be regarded as necessary for scientific practice, or in scientific pedagogy and communication. As mentioned, Salis and Frigg argue that mental imagery is never required. They do, however, recognise that this is ultimately an empirical question.

It would be interesting to consider this in light of recent work on "aphantasia" which is the inability, or reduced ability, to have voluntary, mental imagery. While discussions of the phenomenon can be traced back to Galton (1880), the term was coined just a few years ago in 2015 by Zeman et al. Those taken to have aphantasia can have different experiences. In Zeman et al.'s study, some still experienced involuntary mental imagery, for example, when dreaming. Some did not experience any voluntary mental imagery at all, whereas for others, mental imagery was experienced, but it was significantly less vivid than the control group. Further, there was variation when it came to whether imagery in all sensory modalities was affected, or if it was just the visual kind. There is also discussion around whether those with aphantasia have unconscious (as opposed to non-existent) mental imagery (Nanay, 2018, p. 127). While there are some studies suggesting that aphantasia is more prevalent amongst scientists (Zeman et al., 2020), this research is still in its infancy and there are yet to be studies into aphantasia and scientific modelling and thought experiments.

This prompts questions regarding how "filled-in" or detailed mental images need to be to have the cognitive or epistemic roles that are attributed to them. Is vivid mental imagery more valuable, or can they be highly schematic?[10] How might this vary depending on the example? Nersessian specifies that the mental model view does not involve 'pictures in the mind'; it can be a matter of forming more abstract analogical representations. In making this point, she refers to Bohr who made use of thought experiments but claimed that he was unable to visualise well (1992, p. 294). Furthermore, scientists often make use of diagrams and pictures when presenting models, thought experiments and other scientific representations (Meynell, 2018, 2020; Sherados & Bechtel, 2020). These function as aids to our imagination – they help to direct our attention in the right kinds of way, enabling us to grasp the key features of the described setup more readily.

4 | IMAGINATION, KNOWLEDGE AND CONSTRAINTS

In Section 3, we saw that there are phenomenological similarities between propositional imaginings and beliefs, and between objectual imaginings and perception. Despite these similarities, we (usually) recognise the difference between actually believing or perceiving on the one hand and imagining (in a belief like or perception like way) on the other. The imagination is also often differentiated from belief and perception by highlighting its voluntary nature; we may not be free to imagine anything that we want to, but we are free to imagine things that we know are not the case. By contrast, we are not free to choose to perceive or to believe something. This freedom is part of the value of our imagination as it is what enables us to create and engage with imaginary scenarios but it is also part of why there is scepticism when it comes to the epistemic value of imagination. If, unlike belief and perception, the imagination is not by nature reality-orientated then perhaps it is just not in the business of providing us with knowledge.

Those who defend the epistemic role of imagination have argued that we ought to (and successfully can) put constraints on our imagination. As Kind puts it, 'when we constrain our imaginings to fit the facts of the world as we know them, we are using an epistemic procedure that is much more akin to scientific experimentation than it is to mere flights of fancy'. She adds that if we 'proceed cautiously', we can form beliefs that will 'usually be justified' (2018, p. 244; see also Kind, 2016). Stuart categorises the constraints proposed in the literature into two overarching types. The first, the "logic-based" approach, claims that we ought to constrain our imaginings in a way that accords with the rules of inference (e.g., by making arguments that have true premises and are valid). The second, the "model-based" approach, claims that we ought to constrain our imaginings so that we have an accurate representation of our target system, and the way in which we manipulate this representation should mirror how the target system would change over time (2020, p. 970).

These views seek to demonstrate that the apparent tensions between the imagination's freedom and its proposed epistemic value can be resolved. Skolnick Weisberg draws on empirical research into adults and children's responses to fictional stories to show how our imaginings are substantially grounded in knowledge of the real world. She argues that such research adds support to the claim that we can successfully constrain our imaginings and that this is also promising for uses of imagination in science. However, Skolnick Weisberg also points to the fact that this can have a downside; 'the real challenge is in being creative' (2020, p. 257). Stuart takes this line further and claims that there are epistemically valuable uses of scientific imagination that break the types of constraints typically proposed. For example, Galileo's famous falling bodies thought experiment is often taken to expose an inconsistency in Aristotelian physics but as Gendler (1998) has shown, this is an invalid argument and therefore breaks the "logic based" constraints. A case which breaks the "model based" constraints is Einstein's thought experiment in which we are asked to imagine chasing after a beam of light. When we conduct this thought experiment, we do not have an accurate representation of this situation. For example, we cannot accurately imagine 'what a wave of light traveling parallel to you would "look" like' as we cannot see beams of light (Stuart, 2020, pp. 974–975).

Another line of criticism against the constraint-based views is that in arguing that if the imagination is properly constrained, it can produce knowledge, these accounts expose the fact that it is not the imagination itself that is a source of knowledge. Rather, the argument goes, it is the constraints that are ultimately what matters when it comes to the epistemic value of some act of imagining. This is said to undermine claims to 'special, imagination-based' forms of knowledge (Levy & Kinberg, 2021). But this is perhaps asking too much of a theory of how we learn from the imagination, and settling this issue requires a greater understanding of the imagination's relation to other mental kinds (see also French, 2020b; Stuart, 2021b).

The literature on imagination in science, and especially the more general literature on the imagination's role in learning, has focused on the prospect of imagination as a route to knowledge. But this is too narrow: Science has a plurality of epistemic aims, and the imagination may have other cognitive and epistemic roles. As indicated already, the imagination can aid the formation and development of scientific theories and models. It may also play an important role in scientific representation (Frigg & Nguyen, 2016) and lead to "how-possibly" explanations (Sherados & Bechtel, 2020). In the next section, I'll turn to the imagination in achievements of understanding.

5 | IMAGINATION AND UNDERSTANDING

There are now a number of accounts that discuss the connections between imagination and understanding. For example, Breitenbach argues that the imagination can aid the achievement of unification which she takes as fundamental to understanding. For example, in trying to understand some phenomena, we might "imaginatively explore" ideas that unify it. Breitenbach adds that the imagination is also involved in 'developing, testing, and selecting from among existing theories' as well as working out their implications (2020, p. 79). For Stuart, an achievement of understanding can be due to the creation of 'a connection between some theoretical structure(s) of science and existing knowledge, skills or experience, via an exercise of the imagination' (2017, p. 27; see also Stuart 2016a, 2018).

There is also room for an exploration of the connections between understanding and specific forms of imagination. Many accounts of scientific understanding employ language of "seeing" when articulating what it means to achieve understanding. While the relation between knowledge and understanding is a matter of dispute (see Khalifa, 2017; Elgin, 2017; Grimm, 2011 for discussion) it is widely recognised that understanding requires something over and above merely knowing or accepting some information. One way in which this extra requirement is commonly expressed is in terms of "seeing" or "grasping" some proposition or fact. For example, Grimm states that while we may take it that, say, a model is accurate, 'we might nonetheless not "grasp" or "see" how the various parts of the model relate to one another' (2011, p. 88). Similarly, for Riggs, understanding requires that 'one somehow sees the ways things fit together' (2003, p. 218).

Is this language of "seeing" just a metaphor, or does it reveal some important connection between understanding and our imaginative capacities? Some theories of understanding address this head-on. For example, for De Regt, part of the intelligibility of a theory comes from getting a feeling of the consequence of the theory in a concrete situation (2017, p. 102). And this can involve "seeing" these consequences, that is, imagining them in a visual way. Given that seeing is so central to our experience of, and cognitive interactions with, the world, it makes sense that when we want to go beyond what we can observe directly, we use our visual skills to form mental images (ibid., 257). Likewise, Meynell emphasises that images (mental or otherwise) have a spatial resemblance to whatever it is that they represent. Because of this, they have implicit content that is derived from our knowledge of reality and causality (2020, p. 52).

Meynell offers the most detailed account of the relation between images and understanding. Like de Regt who understands visualization as just one feature that can contribute to the intelligibility of theories, Meynell does not claim that (mental) images are necessary for understanding. Instead, she proposes that we 'treat pictures as the standard, representative content—the characteristic content—of understanding' (2020, p. 40). Todd (2020) also discusses the value of the imagistic imagination in understanding which, he argues, turns on the imagination's connection with affective states including 'aesthetic-epistemic' feelings. Again, we can ask whether such discussions should be limited to visual, mental imagery. Toon (2015) draws on work on extended cognition in psychology and cognitive science to argue that understanding is not just "in the head"; it extends to the body and to external, material devices. If Toon is on the right lines, and understanding, and perhaps specifically, "grasping", is not just a psychological act, then this would have interesting consequences for how the imagination facilitates understanding, and what kinds of imagination play a role.

6 | FUTURE DIRECTIONS

There is now a substantial literature available on imagination in science. While I hope to have addressed the key issues that make up the current debate, I'll end by highlighting other emerging topics and by pointing towards possible developments.

One of the proposed benefits of the Waltonian view is that make-believe is social activity; 'It has an objective content that is normatively characterized in terms of social conventions implicitly or explicitly understood as being in force within the relevant game' (Salis & Frigg, 2020, p. 44). This makes it well suited to scientific thought experiments and models. But the social dimensions of the scientific imagination is yet to be explored in light of the collaborative aspects of inquiry and the division of cognitive labour in science. What would a collective use of imagination in science look like? Can uses of imagination be divided between scientists or between groups of scientists? Given the links between the imagination and creativity as highlighted in the introduction, a constructive place to start might be via accounts of collective creativity in science (Anscomb, 2020; Ritson, 2021; Wylie, 2015). This literature includes a focus on the distribution of creativity within the social order of science which offers a link with an interesting finding of Stuart's (2019a) study of the imagination in two biology laboratories; senior scientists regarded the imagination as far more valuable than those who were at earlier stages of their careers.[11]

We have seen that a dialogue is beginning to form between those discussing imagination in the context of science, and those discussing epistemic uses of imagination more broadly. But what exactly is the relation between imagination in science and other cases of learning from imagination? Some, such as the mental model views and Sorensen (1992) take uses of the imagination in scientific thought experiments to be drawing upon the same cognitive resources that we use in more everyday reasoning contexts. But more needs to be said as to whether there are distinctive demands on scientific uses of imagination and whether there is variation across the different sciences. This could be further explored with reference to emerging views that take imagination to be a skill (Kind, 2021; Blomkvist, forthcoming). On such accounts, the imagination is something that can be controlled and developed with practice. Are scientists' imaginations trained, then, within the context of their disciplines? How does this lead to more reliable or more fruitful outcomes?

Finally, we can ask: What will happen to the imagination in science? Do scientists have more reliable tools that should replace the imagination? Chandrasekharan et al. (2012) predict the "end" of thought experiments; computer simulations also allow for the exploration of counterfactual scenarios yet can handle far more complex situations than the imagination and are therefore more suited to science. Others argue that computer simulations are "opaque" thought experiments which means that computer simulations are more likely to have surprising outputs than thought experiments conducted in the imagination (Lenhard, 2018).[12] Against this line of thought, Arcangeli (2018b) defends the indispensability of thought experiments in science by drawing a distinction between different types of mental simulation, and French and Murphy (forthcoming) argue that thought experiments can be a distinctive source of productive surprise precisely because they appeal to imagination. Furthermore, Stuart (2019b) offers a discussion of the necessity of imagination in machine discoveries in science. But there are many open questions regarding the relations between imagination and computer simulations, the idea that simulations are "extensions" of our imaginative capacities, as well as the possibility of imagination in AI.

The literature on the value of the imagination in science is growing rapidly. It is exciting to see how philosophers of science will continue to explore this fascinating topic, drawing upon a wide range of disciplines, such as epistemology, aesthetics, philosophy of mind, cognitive science, and hopefully HPS and sociology of science, to do so.

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ENDNOTES

[1] This kind of imaginative activity has been labelled the "transcendent" use of imagination and has been contrasted with "instructive" uses that is, those that enable us to learn something new about the world (Kind & Kung, 2016, p. 1).

[2] For more on the issue of whether creativity is subject to explanation, see Kronfeldner (2018).

[3] For further discussion on the relations between scientific thought experiments and models on the one hand, and literary narratives on the other, see Hartmann (1999); Morgan and Norton Wise (2017); Davies (2007); Egan (2016), Elgin (2014, 2017); Murphy (2020a); Arcangeli (2021); Stuart (2021a).

[4] An exception is the Waltonian views of models developed by Frigg (2010) and Toon (2012) that emphasise the propositional imagination, drawing on Walton's notion of "fictional truths". This is discussed in more detail in Salis and Frigg (2020) whose view I turn to below. However, Meynell (2014) offers a Waltonian view of thought experiments which highlights the experiential imagination, arguing that if the make-believe account took imaginings to be of a propositional kind, then it would not be clear how this would differ from Norton's account that thought experiments are just arguments. See Murphy (2020b) for further discussion.

[5] These views are set against the argument view of thought experiments, as advocated for by Norton (1991, 2004). For critical discussions, see Stuart (2016b) and Brendel (2018).

[6] Salis and Frigg favour make-believe over supposition when it comes to characterising the scientific imagination as supposition is not constrained enough for science. They also take counterfactual reasoning to be a species of propositional imagination but argue that make-believe more accurately captures the imagination in science as possible worlds are complete but scientific models are not and because of the difficulties with demonstrating how we gain knowledge from counterfactuals. See Williamson (2020) for a response to Salis and Frigg on this point. Spaulding argues that scientific modelling and theorising involve supposition, that is, 'employing something like the hypothetico-deductive model' instead of the imagination (2016, p. 220). See French (2020b) for a response.

[7] See Kim et al. (2018) for a discussion of imaginative resistance beyond counter-evaluative cases.

[8] Thank you to Erik Curiel for pointing me towards this example.

[9] This therefore helps evade the worry that some models are "unimaginable" as Weisberg (2013) argues as such an objection assumes imagination to include the formation of mental pictures (see also McLoone, 2019).

[10] See Gregory (2020) for an argument that visual, mental imagery can be evidence for possibility when such images are "accurate".

[11] Another issue relating to the social dimensions of science concerns the importance of exercising the "moral imagination" when making value judgements (Brown, 2020). It will be interesting to see how this idea might be integrated with existing discussions of the imagination as presented here. See also Medina (2013) for a discussion of the imagination and imaginative resistance in the context of social change.

[12] For further discussions of the epistemic value of surprise see Morgan (2005), Parke (2014), Currie (2018) and Ritson (2020).

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