Beauty in Experiment: A qualitative analysis of aesthetic experiences in scientific practice

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Abstract

A growing literature in philosophy of science focuses on the role of aesthetics in scientific practice, with the experiment recently recognized for its aesthetic value. However, the literature on aesthetics in experimentation grows out of case studies from the history of science, leaving open the question as to how contemporary scientists experience aesthetics in their experimental work. In this paper we offer the first qualitative, empirical analysis of aesthetic experiences regarding experimental practice, drawing from in-depth interviews with 215 scientists in four countries. We identify six categories of aesthetic experience we find in experimentation, their function, and new questions emerging from our study.

Keywords: Aesthetic Experience, Beauty, Experiments, Qualitative Study

1. Introduction

A growing literature in the philosophy of science focuses on the role of aesthetics in scientific practice. From paleontology (Wylie ((2015, 2021)) and chemistry (Parsons (2012), Ball (2021)), to anatomy (Clarke and Ambrosio (2018)) and thought experiments (Murphy (2020)), philosophers are now attending to how aesthetics affect particular areas of scientific practice. Lately, the experiment has been recognized for its ability to evoke aesthetic responses (Ball (2005, 2021, 2023), Ivanova (2021b, 2022a, 2023), Ivanova and Murphy (2023), Parsons and Reuger (2000)). The philosophical literature on aesthetics in experimentation grows largely out of case studies from the history of science. While such historical analyses highlight important ways in which aesthetic factors feature in scientific practice and the role they play in scientific reasoning, they are insufficient to inform us about whether and how contemporary scientists experience aesthetic features in their experimental work. The question remains open as to whether contemporary scientists experience aesthetics in their experiments in the same ways that are reported in historical case studies, given the diversity of research methods and experimental

practices used today. This calls for an investigation employing alternative methods to address this question in further depth.

In this paper, we analyze the aesthetic experiences of contemporary scientists – physicists and biologists – in experimental practice, drawing from in-depth interviews with 215 scientists in four countries. We find that aesthetics features in contemporary physicists' and biologists' experimental practice in many ways, and plays different roles in their decisions and experiences. In line with findings based on historical case studies, we found that contemporary scientists experience aesthetics when engaging with the phenomena they study in the lab, the design of experiments, the tools and instruments they use, the data they collect and interpret, and in the performance of experiments. Our qualitative study also reveals differences from proposed frameworks using case studies. Particularly, we found that some experienced their daily practices as lacking the creative agency and aesthetic sensibility they encountered in the designing or problem-solving phases of experiments.

Our approach follows a recent trend in philosophy of science to extend philosophical analysis and argumentation beyond case studies and apply empirical research methods. This trend goes back to work by Knobe and Nichols (2017), Stotz and Griffiths (2004) and Stotz (2009), but more recently has gained significant ground, with philosophers of science increasingly turning to empirical methods to address a diversity of philosophical questions (Schupbach 2011, Waskan et al. 2014, Douven and Schupbach 2015, Steel et al. 2017, Chall et al. 2019, Mättig and Stöltzner 2019, Nersessian (2009), Robinson et al. 2019, Stuart 2019, Beebe and Dellsén 2020, Wilkenfeld and Lombrozo 2020, Schindler 2022). We align our approach particularly with philosophers who have urged the discipline to start employing qualitative studies (Wagenknecht, Nersessian, and Andersen (2015)). As recently argued in this journal by Hangel and ChoGlueck (2023), qualitative methods are crucial in philosophy of science as they "can elucidate descriptive and normative components of scientific practice in a more generalizable non-idealised manner" (2023, 29). In accord with Osbeck and Nersessian (2015, 14), we regard qualitative methods as complementary to historical and quantitative methods, enhancing our understanding of a subject. To our knowledge, in the blooming literature on the aesthetics of science there has yet to be a qualitative study looking at the aesthetic experiences of scientists working on experiments. The present study thus offers new insights into those experiences.

We begin section 2 with an overview of the philosophical literature on the aesthetic value of experiments and the different categories of aesthetic appreciation that have been identified through examining case studies. In dialogue with this framework, in section 3 we present our analysis of the empirical data, showing the extent to which it fits with this framework. In section 4 we discuss the insights we obtain from talking to scientists about their daily practices in the lab that have not been brought to our attention through case studies of historical experiments. We also identify further work needed to deepen our understanding of the nature of aesthetic experiences in experimental practice.

2. The aesthetics of experiments: a roadmap of the literature

Since the rise of the experimental method, natural philosophers have appreciated that scientific experiments can elicit aesthetic responses (Ball (2005), Crease (2009, Johnson (2009), Wraggle-Morley (2020). In *The Beauty of Chemistry,* Philip Ball (2021) explores the striking visual beauty that can be observed in the experimental conditions of chemical experiments, arguing that the field of chemistry is particularly influenced by the visual beauty of the subject matter, and that this serves as a great motivator for scientists. In the philosophical literature, Parsons and Reuger (2000) argue that experiments have an important aesthetic dimension, and the history of science reveals that what is aesthetically valued throughout different experimental traditions changes. They argue that while visually pleasing phenomena uncovered by the experimenter were at the forefront of aesthetic appreciation in the 17th century, by the 20th century the focus had shifted to experimental design.

More recently, Ivanova (2022a) has identified several levels of aesthetic experience in scientific experimentation: visual/sensory features; relationship between experimental design and significance; and the creativity and innovation the experimenters used for the conception of the experiment, its instruments, tools and set up. She argues that while visual features can play several important roles in science, e.g., motivating scientists and aiding science communication, they are neither necessary nor sufficient for the aesthetic appreciation of experiments. Rather, the relationship between aptness of design and what the experiment achieves is of particular importance. These kinds of aesthetic values are associated with an intimate intellectual beauty and feeling of achievement. In accord with this account, we distinguish between visual beauty, which is immediately accessible to the senses, and intellectual beauty, which is experienced when one appreciates the design and significance of an experiment.

We start our analysis with a distinction that we find in the philosophical literature. Then, our goal is to see whether our data supports the categories that have been arrived at via case studies, or whether our data points to further categories or different relationships between them. Ivanova (2021b, 2022a, 2003) delineates six different levels at which experiments can be appreciated aesthetically.

a. The subject of study. The phenomena that are investigated under experimental conditions can be visually pleasing. These can be natural phenomena, like cells, light and electricity, or carefully created ones under experimental conditions, like synthetic chemical elements such as the C60 molecule.

b. The instruments and tools used by the experimenter. From microscopes, chemical retorts and particle chambers, to complex structures like the large hadron collider or the James Webb Space Telescope, the tools and instruments utilized in the experiment can display craftsmanship and visually pleasing aesthetic features that can be appreciated in their own right.

c. The experimental design. Experiments are praised for their elegant, economical and simple set up, as well as aptness. Aptness, an experiment's fitness and suitability for a particular goal, is especially important when it comes to experiments of high complexity, like those at the Large Hadron Collider at CERN. Beyond the complex set up and technology, such experiments are appreciated for the optimality of the design as fit for purpose.

d. The process of conceptualising, constructing and running the experiment. There is a parallel between this and artistic production. Experimenters, like artists, use their creativity, imagination and aesthetic sensibility in diverse stages of experimental practice. The scientists that come up with the design and those who carefully carry out the experiment can be praised for their personal skills and capacity in conceiving of the praiseworthy design or delivering important results.

e. The significance of the results. There are a number of possible aesthetic responses to experimental significance, which depend on the nature of the result. Do the experimental results align with expectation, confirming a theoretical prediction? Do they fail to confirm prediction? Do they reveal something new and yet unaccounted for? These various outcomes can generate different aesthetic responses, from a sense of understanding to frustration to surprise. These responses, in turn, indicate an unexplained, anomalous result, leading to productive problematization of extant knowledge and the possibility of further advancing with our understanding of the subject matter. An experiment with a pleasing design that does not lead to a significant outcome lacks the same kind of aesthetic value. Scientists tend to find a deeper aesthetic value in the intricate connection between design and significance. The overall aesthetic value of the experiment can be due to a diverse aesthetic response to its results, depending on whether they are expected or not.

f. The performance of the experiment. The experience of running the experiment can be seen as a process of deep aesthetic engagement. Whether it is because the experiment reveals beautiful phenomena, engages the creativity and innovative capacities of the experimenter, involves designing and crafting, generates a feeling of connectedness to others, or simply engenders a sense of wonder and awe, engaging with the experiment can evoke an aesthetic response.

Let us illustrate the above classifications with a number of historical examples. Consider Léon Foucault's pendulum experiment, for instance, which Crease (2009) considers among the ten most beautiful experiments in science. The experiment was carried out in 1851 and aims to demonstrate Earth's rotation around its axis. Foucault hung a heavy brass weight from a long cable fixed to the inside of the dome of the Pantheon in Paris and set it in motion. The brass weight then swung slowly back and forth, tracing lines in the sand beneath it. In due course, the experiment revealed that the traces in the sand were not aligned, due to Earth's rotation beneath the pendulum.

We can find some immediate, visually pleasing features in this experiment. The pendulum is visually beautiful, and like many other experimental instruments, it has its own aesthetic value. Scientific equipment can be beautiful and artistically crafted, from chemical retorts, prisms and microscopes, to complicated structures built in laboratories, the instrument of the experiment itself can be a product of ingenuity, creativity and craftsmanship. Unsurprisingly, many old instruments are hosted in contemporary museums and art galleries displaying their visual beauty. The phenomena studied in the experimental set up, like copper sulfate crystals, protein structures, rainbows produced by prisms, and the microscopic structure of cells, can be beautiful too. But these are the visual aspects of the experiment, and while they are important and can offer motivation and awe to the experimenter and those who get to experience the experiment, what carries a lot of aesthetic significance is the element of design and significance, as argued in Ivanova (2022a, 2003). Using the above distinction between visual and intellectual beauty, we can appreciate that what made Foucault's Pendulum a beautiful experiment goes way beyond its visual beauty; the experiment has high aesthetic value because of what it showed and how it showed it. The experiment demonstrated the effects of the earth's rotation, something that has been disputed for centuries, and it did so in an elegant, creative and apt way, using economical materials to deliver its results. The pendulum itself might be beautiful, but the ultimate beauty of the experiment is this intimate connection between its significance and its design.

To illustrate further the aesthetic value found in the interplay between design and significance, consider also the famous Messelson-Stahl experiment, designed to demonstrate how DNA replicates. This experiment bears the title of 'the most beautiful experiment in biology' (Holmes (2008)), the reasons for which have to do with the intricate design well suited for its purpose. Messelson and Stahl designed a highly apt experiment, using new techniques for labeling the genetic material, and were able to study how the genetic material changed in the next generations, after feeding bacteria heavy nitrogen first, then light nitrogen, and comparing the density of the genetic material though the next generations. The results were considered highly beautiful because they were conclusive and clear – they showed which of the three proposed hypotheses (conservative, semi-conservative and dispersive) were correct – making this experiment an example of a crucial experiment in science (Ivanova 2021a).

Beautiful experiments, however, are not always appreciated for their beauty because they fit our expectations by confirming a hypothesis or detecting a predicted phenomenon. While confirmation and detection are two significant achievements that can certainly give the experiment aesthetic appeal, some experiments deliver results of great significance when they deviate from expectation. Some null results, or failures to detect, can have profound significance for our understanding. As Ivanova (2022a) argues, experiments like the Michelson-Morley experiment or the LHC ATLAS and CMS experiments are beautiful because of their highly apt design for purpose, which afforded their producing null results of great scientific significance. Failure to detect the ether forced great advances in physics in the early 20th century, leading scientists to question established theory and eventually offer support for the special theory of relativity. In contemporary physics, failure to detect supersymmetric particles is forcing the physics community once again to revisit its central theoretical assumptions. As Hossenfelder (2018) has argued, this is putting a question mark on not only the physical theory that predicts these particles, but also the very fundamental principles that have guided the community in the last century in the development of our physical theories: the aesthetic principles of naturalness, symmetry and simplicity.

As we have seen, current work in philosophy of science identifies a number of components that feature in aesthetic experience in the context of scientific experimentation. These include: the visual features, which scientists can find motivating and inviting engagement; the design, which shows elegance, economy and aptness for purpose; the significance, wherein the results are important in advancing our understanding; the creative and innovative thinking of the experimenters, embodied in designing a well-suited-for-purpose experiment that advances our knowledge; and the performance as parallel to artistic performance.

Whereas this extant literature is grounded in historical case studies, our contribution is to examine how contemporary scientists experience aesthetics in their experimental practices. We ask whether the above framework fits contemporary scientists' experience, or whether it is too inclusive or limited. After describing our methodology and analytic approach in the next section, we present our findings. We then discuss where our findings fit with the existing framework, where we see interesting deviations, and what further questions emerge from our qualitative analysis that need philosophical attention.

3. Methods

To examine scientists' aesthetic experiences in relation to their experimental work, we draw on data from interviews with contemporary physicists and biologists in India, Italy, the United Kingdom, and the United States. Between July, 2021, and January, 2022, a team of researchers

including two of the authors conducted a total of 215 in-depth interviews as part of a broader study about scientific practices[1].

Interviewees were sampled from a pool of scientists who completed a survey designed to be representative of physicists and biologists working at Ph.D. granting academic institutions and national labs or research institutes in the four countries. The survey included a question asking whether the respondent would be willing to be contacted for a follow-up interview. Interviewees were recruited from those who agreed to be re-contacted, and were sampled for diversity with respect to country, gender, discipline, and position. Interviews with respondents in India, the United Kingdom, and the United States were conducted in English. Most interviews with respondents in Italy were conducted in Italian, then translated into English. All but one interview were conducted via Zoom. On average, interviews lasted 71 minutes, and ranged from 30 to 120 minutes. Interviewees were given a gift card valued at the equivalent of $50 USD in thanks for their participation. The study was reviewed and determined to be exempt from regulations governing Institutional Board Review (IRB) by the IRB at the University of Notre Dame. All names of research participants used in this paper are pseudonyms. Interview demographics are shown in table 1.

Table 1: Interview Sample Demographics

Characteristic	N	%
COUNTRY		
USA	56	26
UK	53	24.7
India	51	23.7
Italy	55	25.6
GENDER		
Female	103	47.9
Male	112	52.1
DISCIPLINE		
Physics	110	51.2

[1] For more information on the broader study and key results, see Jacobi C. et. al. (2022), Jacobi C. et. al. (2023) and Vaidyanathan, B. et. al. (2023).

Biology	104	48.4
Other	1	0.5
POSITION		
Postgraduate Student	51	23.7
Postdoc	50	23.3
Research Scientist	13	6.0
Junior Faculty	35	16.3
Mid-Level Faculty	25	11.6
Senior Faculty	30	14
Other	1	0.5
Left Academia	10	4.7
Total	**215**	

For the purposes of this paper, we focused on the portion of the interviews about the role of aesthetics in scientific experimentation. Interviews were semi-structured, including questions such as, "To what extent would you say beauty plays a role in the actual practice of science, for example, designing a project, conducting experiments, or in communicating or teaching science?" Interviewers followed up to interviewees' responses to such questions by probing further into what scientists meant by their responses and eliciting examples. With the assistance of a software designed to facilitate qualitative interview analysis, ATLAS.ti, we identified and closely read all passages from the interviews relevant to experimentation that came up in the course of the interview.

To analyze the data, the authors first summarized themes that emerged from an inductive reading of relevant passages. Because we wanted to understand scientists' aesthetic experiences on their own terms, we counted as aesthetic anything the scientists themselves suggested they experienced aesthetically. Upon discussing the emergent themes as a group, the authors discovered that each of these themes could be incorporated into one of the six categories of aesthetic experience in experiment theorized in extant philosophical literature. Next, revisiting the data through the lens of this six-part typology, Authors 2 and 3 identified examples of each type, which we present in what follows. Discussing these examples as a group, the authors affirmed that the six-part typology arrived at by historical case studies can be largely reinforced by the qualitative study, while also identifying where the data deviated from the extant framework and questions for further investigation emerged. Specifically, the authors identified that when it comes to performance, the data indicate that the daily practice of running

experiments is characterized less often by beauty than by messiness and mundanity in scientists' experience. This iterative process of engaging the data and developing the typology left us with the six categories of beauty in experiment described and illustrated below.

4. Results

a. Subject of Study

As we discussed in section 2, scientists as far back as the 17th century noted that the visual beauty of the phenomena they studied was a source of aesthetic pleasure and motivation for their pursuits (Parsons and Rueger 2000), Ball (2005)). Here we show that the visual features of the experiment remain an important source of aesthetic pleasure for contemporary scientists, though not the only one, as we shall see.

The physicists and biologists we interviewed encounter visual beauty in what they study in experiments, whether in the subject itself or in the images involved in working with it. The beauty of color in particular was emphasized both by physicists who worked with light and biologists who worked with cells.

For Alice (Physicist, Associate Professor, Italy), who studies quantum optics, the visual aspects of experiments involving light bear aesthetic "appeal." "Light," she says, "allows us to see beauty with our own eyes." By "beauty," Alice here refers to the "colorful events" light brings into view. Not only does Alice appreciate such visual beauty in its own right, counting herself "very lucky to be working with light," but she also leverages it in teaching and communicating her work, for she finds it bears both motivational and explanatory significance. "[W]hen students come to our laboratory, we know what experiments and phenomen[a] can get them impressed, interested, which obviously helps the explanation part." When tasked with preparing a video about her research to show to a more general audience, Alice "decided to show something visually appealing." In her view, visual beauty appeals to interest; being interested, in turn, facilitates understanding the explanation at issue.

Sandhya, a Professor of Biology in India who works with cells, also finds what she studies visually beautiful. Cells marked with fluorescent colors and seen beneath a microscope yield "artistic views." Live-cell imaging makes it feel like watching "a Star Trek movie," she reports. "You see the bacteria swimming around and you see beautiful dendrites and then you see it is getting inside something and if somebody can convert it into a movie, it will be just like a movie because the structures are like that." Sandhya's case speaks to the way technology makes available certain kinds of visual beauty; live imaging makes it possible to see the dynamic, visual beauty of cells.

Lois, an Assistant Professor of theoretical Physics in the UK, does not run experiments herself, but finds beauty in the "microscopy images" produced in experiments by her colleagues and students. One of her students once produced images that were "really beautiful, literally beautiful," so much so that she encouraged him to submit them to an art exhibition. The fact that she finds beauty in her colleagues' work speaks to the role of collaboration in occasioning encounters with beauty in science.

b. Technology

In section 2 we discussed how the beauty of the experiment can often be due partly to the beautiful tools and instruments used in it. Whether we consider an elegant instrument such as the interferometer and the air pump or contemporary large particle colliders, scientists have reported finding beauty in the diverse instruments they use. We find that contemporary scientists also find beauty in the tools they employ in experiments. The physicists and biologists we interviewed pointed to diverse laboratory tools as subjects of aesthetic appreciation.

Charlotte (Physicist, Full Professor, USA) takes aesthetic pleasure in the detectors her lab puts together. "Physically, it's very beautiful," she says. "What's just really beautiful about [the device]," she continues, "is there's so much detail in it that matters." Even a "cross section of [it] would just be incredibly rich." Charlotte is so fascinated by such detail, she feels the need to show it to others. New students become her captive audience. "[I]t's terrible," she apologizes. "When new students come into my office, I need to tell them every single thing that's rich about the actual assembly. So the underlying physics of this brand-new technology is super cool." Charlotte's felt need to show new students the rich detail of the devices she works with speaks to a more general point: aesthetics overflow an individual scientists' experience and motivate them to share these experiences with others.

Like Charlotte, Francesca (Biologist, Ph.D. student, UK) finds beauty in the way lab equipment is built to suit its purpose. "[T]here is something about lab equipment as well," Francesca says, "that I think it can give you purpose in what you're doing and you can recognize as beauty just because it's so specific and organized and everything has got purpose." But there is another sense in which Francesca finds beauty in lab equipment. Not only is the equipment beautiful for its aptness. It is also beautiful in that using that equipment draws you into the community of inquirers who have used the same sort of tools before you. "And then you go to the little glassware," Francesca says. "[T]hat has gone through a history of all of the people [who] have done science with the similar kind of equipment before. And it's just a whole grandiose, we are all into this together using these things. And it might be just an object, but if you look at it in that context, I think it is quite beautiful and awe inspiring in a certain way." Francesca finds the sense

of connection to community she gets from using the same kind of lab equipment as other scientists a beautiful, even “awe inspiring” experience.

What Sandra (Physicist, Ph.D. student, UK) finds beautiful about technology is that the concepts behind their creation actually work: “with superconducting magnets and dilution refrigerator which uses properties of liquid helium, like I still do really appreciate the beauty of that, these simple concepts that really work.” For her the “beauty” in technology is in that and how it works.

c. Design

As discussed in section 2, prior philosophical work on aesthetics in experimentation revealed that the design of an experiment is central to its aesthetic valuation. In accord with this literature, we found that contemporary scientists appreciate experimental design that is simple, elegant, and apt for purpose, that is, the way their set up is suited to achieving a particular goal.

Rishi (Biologist, Associate Professor, India), equates beauty with simplicity. In his view, more parameters increase the probability of error, and make it impossible to know which one is responsible for the results. “The more complex stuff you do,” Rishi says, “the more chances there are to screw up. And you never know if X and Y are responsible or X, Y and Z are responsible.” Complexity in this sense is counterproductive. Simplicity, by contrast, is beautiful in that it contributes to experimental success and the scientific understanding that can be derived from it.

Max, a Research Scientist in Physics in the UK, echoes Rishi’s appreciation of the efficacy of simplicity in discussing what he sees as “ugly” experiments. “I think if you've made a theory that is overly complicated or ugly,” Max says, “like particle physics has standard models where you just add in random parameters to try and make it fit and things like that – that's kind of ugly.” Max sees simpler experiments as more effective. “So if I design something, and I go to my PI, and it's got an extra mirror, we cross out the mirror, we’re not discussing it, because it's not needed. That simplification, I think, … makes it easier to work with, because it's simpler, and it's therefore more aesthetically pleasing, because I could understand it just by looking at it.”

Some scientists find beauty in experimental “elegance.” Ben, a Full Professor of Biology in the UK, understands elegance in terms of efficiency, which makes experiments more replicable. Ben offers the example of testing vaccines in a certain population. “Most of us as scientists don't have the funds to throw 40,000 replicates at a particular hypothesis. We have to do it with 40 replicates or 400 replicates if we're extremely lucky. So that requires a great deal of elegance in terms of how you efficiently design that experiment to be done with all the key components

present, and to provide a statistically solid test of your hypothesis but with an efficient use of resources."

Other scientists find beauty in experimental aptness, measured in terms of the fit between design and purpose. Francesca, the UK Ph.D. student in Biology who spoke of the beauty of lab equipment like glassware, thinks aptness is key to a beautiful experiment. Indeed, it is what gives value to the more mundane aspects of experimental design. The experimenter may be "just gluing and siliconing things together," Francesca says, "but they serve the purpose and they're a perfect circle or something like that. I think everybody who is going through that process will think at the end that it is beautiful."

Brittany, a Ph.D. student in Physics in the US, echoes Francesca's emphasis on the aesthetic value of the aptness of experimental design. "We know what we want to look for," Brittany says, "and we want to make sure that whatever we're designing to look for those quantities is specifically designed." She continues:

> So it was very well designed and very meticulously designed from that sense, if you want to call that beauty, very detailed and a lot of meticulousness going into something. But I think the focus is more on, 'Are we able to get the elegant, beautiful solution? Will things work out?', not necessarily 'how we design the experiment is nice.'

Brittany's focus is not on the visual attributes of the experiment, but on the fit between design and purpose, the importance of constructing an experiment well to obtain significant results. In this sense, even here we see emphasis on the intellectual beauty revealed in a good experiment.

By contrast, Holly, an Assistant Professor of Biology in the UK, says that beauty is not something she considers in experimental design; "In experimental design, certainly in my field, beauty isn't something I think about or even recognize." But, continuing, she acknowledges that a well-designed experiment can be considered beautiful: I mean aside from, you know, a well-designed experiment, you know, you could call it beautiful."

d. Creativity

Our study reveals that scientists often see the work of conceptualising and constructing experiments as analogous to making art, in that it requires creativity, imagination and aesthetic sensibility. Some respondents also draw an analogy between experimentation and cooking, both

of which, in their view, involve deviating from prescriptions in order to explore possibilities and produce something original.

Francesca, the Ph.D. student in Biology who spoke of her aesthetic experiences of lab equipment and experimental design, says that "the element of research that I think I enjoy more is actually the experimental design. So coming up with new treatments, orders and making sure that everything is balanced." This highlights the aspect of creativity required to come up with something new and also the craft of keeping the balance, which she does with color coding spreadsheets and seeing the visual beauty that emerges. "I tend to do that on spreadsheets with, like, color coding things, and I actually find that quite a soothing exercise and when I do get a balanced spreadsheet, that, to me, it looks beautiful."

Jennifer, an Assistant Professor in Biology in the UK, as well as an artist, sees science as an art form. Designing experiments is a skill, in her view, that needs to be developed and practiced just as with any artistic craft. "To me, there's sort of the same thing: you're perfecting a craft." She continues:

> It's not just 'test this and this and see if this happens.' There's intricacy and it's just really well thought out… you don't just know how to design an excellent experiment that is really suitable for your particular subject of study. Because that's a skill that you need to get better at over time and that's not an independent thing. You have people who can advise you and help you and you learn based on those things. It's to do with sort of honing your craft to getting better at experimental design."

Jennifer thinks that experimental design needs to be learned and practiced, since it's not just a matter of putting things to the test and waiting for results.

For Hili (Research Scientist, Physicist, UK), designing code brings out the creative aspect of experimentation. She underscores this with an analogy between programming and architecture. "So you don't just go and code; it's a bit like being an architect for a building," Hili says.

> You would always make plans first before you go and build something. So it's the same with code, like you have to do your architectural plans first and then you would write your code. You wouldn't just go and write it because it won't be very good code.

The "designing bit, " Hili says, is "beautiful."

Stefan, an Assistant Professor of Biology from the UK, finds beauty in his job as a scientist when he sees his projects grow from an idea. He compares his work to successfully cooking based on a recipe,after you have tried and failed several times. “It's always when you have an idea, a hypothesis and you cook up a recipe and then after 10 fails it works, and so for me, that is like the beauty. And for me it's beautiful in that sense because I came up with that.” For Stefan, beauty comes from the realization that he himself has been able to come up with and develop an idea.

Paulo, an Associate Professor of Biology in the US, similarly compares doing an experiment to making a new recipe, especially when you need to adapt the recipe so you can make it with the ingredients that you have in stock.

> A lot of people cook supper like they looked at the recipe on the internet and they need exactly those ingredients and stuff like that. And you can do it, and it's going to turn out well, but something there is also exhausting and that makes people not do that same recipe many more times. You feel a little bit you were just executing. And there are ways to actually be super creative in the kitchen, I think. When you just deal with the ingredients you have, you don't really go to do that special thing. You can turn it around and stuff like that. And that creativity again, I think it's super satisfying.

Another US-based Biologist, Javier, a postdoctoral fellow, evokes the cooking analogy from another angle, but in a way that reinforces Paulo’s point. To Javier, running experiments as if one is closely following a prescribed recipe feels rather uncreative.

These comparisons between cooking and experiment put emphasis on the constraints these processes entail. Many times there are only certain materials or resources available, and knowing how to put them to work for the purposes of the meal or the experiment requires creativity, which many find intellectually and aesthetically stimulating.

e. Significance

In section 2 we discussed how experiments that are regarded as beautiful often showed something very important: they delivered significant results. Our study reveals that contemporary scientists also ascribe beauty to experiments in virtue of their significance for advancing knowledge. Experiments advance knowledge both when they do and when they do not bear out a prediction. Confirming results aligning with theoretical expectation are appreciated aesthetically but so are results that reveal entirely surprising phenomena or, on the contrary, produce null or anomalous results that productively challenge assumptions.

Ben, a Full Professor of Biology in the US, underscores the beauty of significance in the following exchange. The interviewer asked, "Could you have a beautiful experiment that actually didn't show anything meaningful?" In response, Ben said, "No, I don't think you could." He explains:

> Fundamentally, the experiment [has] got to test the hypothesis and I suppose that hypothesis has to be something that's worth testing. So if you design an incredibly beautiful experiment to test an uninteresting hypothesis, well, it's kind of [a] total waste of your time, isn't it? And therefore by definition it's not elegant or efficient or therefore beautiful. So yeah, it's got to produce not just usable results but important results.

For Ben, significance is the *sine qua non* for a beautiful experiment.

Whereas Ben emphasizes the importance of significance in general for an experiment to be beautiful, other scientists ascribe beauty to particular kinds of significant results experiments can yield. James and Nick, for instance, find beauty in positive results. James, a postdoctoral fellow in Biology in the UK, recollects his "fascination" during an experiment involving bacteriophages, which are viruses that infect and replicate within bacteria. "It was really fascinating to see the theory that had been in writing, being, you know, kind of proven in my own experiment," he said. For him, "it was fascinating to see how actually bacteriophage could bring some results in eradicating infection."

Like James, Nick, a Ph.D. student in Biology in India, emphasizes the beauty of positive results, but in a more general way.

> [W]hen theory matches experiment, when you make an elaborate theoretical explanation or a theoretical model that says, you should see this if you do this experiment. And when you do an experiment and when you see that there is a correlation between what you expect and what you see, I find that very beautiful and very profound.

Positive results are not the only kind of significance to which scientists ascribe beauty. Scientists also see beauty in negative results, as is the case with Meera (Biologist, Research Scientist, India). Meera says:

> [A] lot of people think that negative results are not beautiful. But I believe in science, even negative results can give you some kind of reasoning for the other person to

> progress. So that is what I always feel, that in science nothing is positive-negative; it all depends on what questions you are putting out. Because maybe some results you put out which you think are negative, it might be a good goal for another scientist to carry out that stuff and see that it might work out in a very different way. So for me, science is itself very beautiful.

Hearing this, the interviewer clarified, "And the beauty is in finding the answer, whatever it is?" Meera replied: "It is, definitely." To Meera, even negative results can be beautiful if they show the limits of extant scientific knowledge, indicating where there is more to learn.

In this respect we see that both positive and negative results can be beautiful kinds of experimental significance. In addition, experimental results can often be surprising, whether indicating something completely unexpected or by not aligning with theoretical expectation. In such cases, scientists found beauty in unexpected results that prompted them to try and understand how to interpret and accommodate the results, as Dennis and Timothy emphasize.

Dennis (Biologist, Postdoctoral fellow, USA) shares an anecdote illustrating the beauty of surprising findings that occurred the week just prior to our interview. He had been training a graduate student on observing tumor samples from mice. "We were just looking to see if the markers that we were studying were present on the sample." Suddenly, through the microscope they noticed "these weird spherical structures in the barter of the tumor." The graduate student asked, "Well, what is this?" Dennis replied, "I have no idea what the hell is this and I have never seen this in my life." The two of them then looked at other parts of the tumor, and observed a pattern. "So it all started to seem very logical and too much, too good to be true because it was something so bizarre." But then they checked other tumors, and found evidence of similar structures there. "This was very exciting." Dennis told the graduate student to prepare images to show their P.I. the next day, and they started to envision other experiments to validate what they found. "The fact that we can build a story on top of those images, and [they] could actually be something very cool, it's exciting, right. Yeah. And it's beautiful."

Underscoring the beauty of surprise, Timothy (Biologist, Assistant Professor, USA) shares:

> [P]eople like to feel reassured that they know what's going on, and so you make a prediction, you spend a lot of time coming up with an idea and working hard and then having that satisfaction that you prove it right. That's there, but also that in some cases, I mean, it sounds, maybe, cliché, but you've sort of uncovered part of nature, like you've made a discovery that no one else has seen before or you presume no one else has seen before, at least no one has reported it, in a sense also exciting. Again, as an experimental

biologist, those moments are pretty few and far between and so that's also the roller coaster of, like I'd tell people, of science. So you're at the high, you're enjoying it and the fruition of all your labor.

f. Performance

In historical treatments, experimental performance is often presented as a process of deep aesthetic engagement. While some contemporary scientists experienced experimentation in this way, their aesthetic responses more often derived from the way in which a well-run experiment speaks to aptness of design, or promises significance or achievement, than from actually performing the experiment per se. Indeed, for some scientists, the daily practice in the lab is often anything but aesthetically pleasing.

The way Preeti, a postdoctoral fellow in Biology in India, experiences beauty in experimental performance illustrates the way which the aesthetic of running an experiment derives from witnessing its aptness for purpose. “I find it very beautiful,” Preeti says, “how every step leads to another, like I really like planning my work properly so that least effort goes into actually performing the experiment. But, if your planning is properly done, that gives me satisfaction also and I really like the whole procedure, like planning everything and then doing it, that thing, micromanaging while conducting any experiment. I really like that.” What evokes her aesthetic response during experimental performance is seeing how things go as planned.

While experimental performance evokes a sense of beauty for Preeti, others described the actual process of experimentation or data collection as dull, boring or messy.

“If anything,” says Peter, a postdoctoral fellow in Physics in the UK , “I would describe the real practice of science as ugly or hideous.” His explanation underscores the monotony that often accompanies the process: “On the first day of my PhD,” Peter says, “my PhD supervisor said to me, ‘Ninety-five percent of doing a PhD is redoing what you did yesterday slightly better or slightly differently. And when you get really good at it, that goes down to about ninety percent.’” Peter’s supervisor’s advice rings true in his experience. “Sometimes it can be enjoyable, but there is an awful lot of boring drudge work, frustration, cursing, swearing, like I'm sure there is in any developmental job and beautiful is not a word I would use at that point.” At the same time, Peter does find it “exciting” to begin a project and “see the endgame of where I want to go and I think this would be awesome.” He also finds it gratifying to think “Hey, this will do my reputation wonders when this is out there. This is potentially something that will get well-cited.” Seeing the potential significance and achievement the experiment can bring evokes aesthetic responses, but in Peter’s experience actually doing the experiment is quite a drudge.

Like Peter, Javier, the US postdoctoral fellow in Biology who evoked a cooking metaphor to express the creativity involved in experimentation, finds experimental performance rather mundane. “There's not much room to be creative,” he says, “when you're pipe fitting five microliters of some substance into another substance.” It is telling that Javier does not find beauty in running the experiment, as it leaves little room for “creativity.” His comment implies that, for him, feeling creativity is an aesthetic experience.

Felicity, an Ecologist from the US who left academia after completing a postdoctoral fellowship, experiences the actual process of doing science as messy. “I guess coming from ecology it's such a major thing because all we do is pretty ugly because you've got this beautiful planned fieldwork that should work magnificently, and then that day was raining so you're missing data and your data set is a complete mess, it's not beautiful by any stretch of imagination.” As an ecologist, the complexity of the conditions Felicity works in brings to the fore the messiness of scientific work.

Our results show that while experimentation can evoke aesthetic responses itself, these often derive not from actually running the experiment but from what doing so might lead to, whether it be revealing aptness of design for purpose, significance, or achievement. Experimental performance in itself was experienced as mundane, boring, and messy, when seen as following prescription rather than involving creativity in problem solving situations. Together, these findings underscore the importance of other aspects of experimentation as sources of aesthetic appeal.

5. Discussion

Our interviews reveal the diverse ways in which contemporary scientists experience beauty, and aesthetic experiences more broadly, in the context of scientific experiments. In this section we draw some lessons from these interviews, given the framework we introduced in section 2, and identify a number of questions emerging from our study for future pursuit. Let us start with the idea that beauty can be immediately accessible to the senses, visual, and more intimate, intricate and intellectual. This distinction between visual and intellectual beauty is clearly at play in the experiences of the scientists we interviewed. For many, visual beauty was associated with great satisfaction, generating fascination and motivation to explore nature, to understand the subject matter they are experimenting on, to engage. Unsurprisingly, many also saw visual beauty as a great tool for science communication and teaching. We have seen this appeal of visual beauty in communication of scientific results throughout the history of science. From the public performances of experiments with the air pump or the public spectacle of Foucault’s Pendulum we discussed in section 2, to the recent dissemination of space images by the National

Aeronautics and Space Administration (NASA). The latter example shows the power of beautiful images to fascinate and awe the public, and the importance of appreciating that science can be a source not only of epistemic achievement but also of aesthetic experiences (Ivanova (2022b)). NASA used the images generated by the James Webb Space Telescope in an effort to communicate to the public what this complex instrument, several decades in the making, has enabled science to achieve, sharing this moment of discovery.

Our interviews further unveil the importance of intellectual beauty in science, the beauty that is revealed through systematic engagement and understanding of the subject matter. In the lab, scientists experienced beauty when designing effective experimental set ups, tools and instruments to achieve their goals. They experience deep beauty when encountering a well-designed-for-purpose experiment. Minimizing materials, making an experiment economical, elegant, simple was praised systematically as constitutive of a beautiful design. But there was also care for the significance of the experiment: a beautiful experiment is one that is well suited for purpose. Our interviews revealed that the intuition discussed earlier that an intimate beauty is felt when appreciating the relationship between design and result, is shared by many scientists. The scientists we interviewed claimed that insight is the ultimate aesthetic experience science can lead to, that beauty is found in that moment of discovery when things fit together and we uncover something new or profound that will advance our understanding. This deep aesthetic experience was connected to a sense of accomplishment, or the achievement that comes from creating the set up that will deliver a significant result that advances our understanding.

Our study focuses on two groups of scientists: biologists and physicists. The choice is conscious; often when discussing the aesthetic values prevalent in each field, it is claimed that physicists and biologists operate with different sets of aesthetic values (McArthur (2021)). In addition to recognizing that different scientific areas can have different aesthetic sensibilities, a look at the history of science reveals that across different theoretical frameworks scientists can value different aesthetic features (McAllister (1996)). Our study helps us gain novel insight directly from practicing scientists on the nature of their aesthetic experiences. Is there homogeneity or diversity of aesthetic experiences in the data we collected? One important insight that comes from our study is that the categories that were produced by looking at case studies in biology and physics matched the data from our interviews. The aesthetic values experienced by the scientists we interviewed fit within the six categories, which seems to at least suggest that despite the changing nature of scientific experimentation, the sources of aesthetic experiences are continuous with that of other traditions and timeframes. We also see that while we would expect biologists to find visual beauty more important, physicists very much valued it too. We also see that there is an emphasis by both groups on the ultimate intellectual beauty experienced in insight, when a well-designed experiment produces significant (whether expected, surprising or disruptive) results.his experience often carries with it a sense of accomplishment. As such, our study illustrates both the diversity of the aesthetic objects of appreciation and diversity of aesthetic responses, while also identifying important overlaps and consistent categories. While

each individual category is connected to experiencing beauty, our interviews reveal that scientists feel a deeper, more intellectual, sense of beauty when they accomplish a significant result through a well-designed experiment.

Some of the scientists we interviewed also talked about aesthetic experiences more broadly. They reported awe and wonder in experimental practice more generally and feeling connected to others through scientific investigation. They found that working with instruments that have a history behind them, improving an experimental method which has been designed previously by others and to which they are adding, is a collective form of advancement that generates aesthetic experiences. Whether it is by improving the tools and instruments or the experimental set up, or continuing a previously pursued project, this historic connection to the work of others was a source of awe, a feeling of smallness in becoming part of history. There is also emphasis on the idea of collective creativity, an idea particularly relevant in science today where scientific products are a result of large collaborative initiatives.

An important aspect of the aesthetic experiences of scientists in their experimental work that we found in the study concerns the aesthetic value of the performance of the experiment. Here we were able to gain novel insight into what these experiences are like. While some scientists reported the performance of the experiment to be aesthetically engaging and to have a positive aesthetic dimension, others saw it as lacking or having negative aesthetic value. For some, actually performing an experiment was uninteresting, uninspiring, or messy; it either was not associated with an aesthetic experience at all, or was seen as a negative one. But we gain important insights from these claims too. Those who argued that daily life in the lab is anything but a source of aesthetic experiences revealed, through their emphasis on their felt detachment, that what would be a source of such experience is having the opportunity to be more creative and feel a sense of agency in the experimental process. These claims reveal that an important source of aesthetic experiences in experimentation comes from the exercise of creativity in problem solving. Not receiving an expected result was seen as a beautiful experience because it allowed for creative thinking when the scientist had to decide what to do next and felt involved in the process of discovery. These comments suggest that aesthetic experiences were associated with an overall sense of agency in the running of the experiment, which might be lacking in certain experimental setups such as those involving big collaborative teams.

This leads us to consider the broader nature of aesthetic experiences in the lab. In section 2 we discussed the idea that aesthetic experiences can be diverse; they can be beautiful, inspiring awe and wonder; and they emerge when the result aligns with expectation. But they can also have a disruptive and more disturbing nature, when we encounter surprising or even anomalous results. The latter results are probing in a way the former are not, they invite further inquiry, and can lead to conceptual advancements in the field. When scientists associated the lack of these experiences with dullness and ugliness, they were explicitly admitting that beauty is to be found in these

profound moments where we get to ask questions, prompt our creativity and ultimately advance our understanding by devising new ideas, new tools, new experimental designs.

Our investigation gives rise to further questions that deserve more attention from philosophers, sociologists and historians of science. How can we understand the notion of collective creativity? Standard accounts of creativity and imagination, analyzed recently in Kind (2022), take the unit exhibiting these capacities to be the individual, but can the creative process emerge from the collective? If so, what might this mean for how we should conceptualize what creativity is? How is collective creativity related to the aesthetic experience of agency and being involved in the construction and running of a big collaborative experiment? Furthermore, is there a more prominent role for ugliness in science? Ritson (2020, 2023) argues that sometimes experimenters might consciously look for ugly results in hopes that those results would prompt the advancement of a field. Ritson focuses on the current disputes on the standard model, where many believe the community has stagnated. How should we understand the place for ugliness in science more generally, and can it contribute to scientists' overall aims, whether epistemic, aesthetic or other? Furthermore, is there space for negative aesthetic experiences and are these accounted for by existing philosophical accounts in the literature? For instance, Arcangeli and Dokic (2020) have identified pleasing aesthetic experiences with ease of understanding or processing fluency and disruptive ones with disfluency processing, being ultimately fruitful experiences to have in the advancement of knowledge. More research is needed to assess whether the accounts we have identified here adequately capture the diversity of aesthetic responses in the lab. We hope our study will fuel further investigation into these important questions and further support the move towards using qualitative methods in philosophy of science when addressing philosophical questions concerning scientific reasoning and practice.

In the present article, we have restricted our focus to the general themes and types of aesthetic experience in experimentation that emerge from our interviews. This is not to suggest that such experiences are evenly distributed across social locations such as nationality, gender, and position. While such differences in aesthetic experiences likely exist, our interview sample in this article does not allow us to make statistical generalizations. Such differences in aesthetic experience in experimental science remain an important topic for future research to pursue.

5. Conclusion

Current understanding of aesthetics in science has been driven by work examining historical case studies. While important, enhancing our understanding of aesthetic experiences in scientific practice calls for alternative methodologies in order to gain further insight into existing questions and identify new ones. We have shown how the literature on aesthetics of science can be enriched by empirically investigating the aesthetic experiences of scientists in regards to experimentation. By drawing on qualitative interviews with 215 biologists and physicists about their daily experiences, we not only put to the test the theoretical framing arrived at by studying

historical experiments but identify important new aspects of what scientists aesthetically value . We found that scientists do find aesthetic value in the six categories we discussed in the framing of our paper: the phenomena under study, the instruments and tools, the experimental design, the experimental results, the creativity it calls for in the design and implementation of the experiment, and, last, in the performance of the experiment. We saw that we can indeed draw a distinction between the more immediately accessible, visual beauty and the intellectual beauty of the experiment, and that the latter is highly regarded and serves different functions compared to the former. Scientists found a well-designed experiment that accomplishes something important, whether positive or negative, to be a source of a special kind of aesthetic experience, to find beauty in the process of discovery. But what our qualitative study also reveals is that often the lack of such features can make the daily experience in the lab lacking an aesthetic dimension. We learned that scientists experience beauty in the feeling of involvement, of agency, being creatively involved in resolving problems. In that sense, in the present article we have not only offered a novel study of contemporary scientists' aesthetic experiences in experimental practice but have identified important new questions for further investigation. Our work invites more systematic investigation into collective creativity and the sense of agency involved in the design and running of experiments and how this relates to the sense of achievement scientists value so highly.

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