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Aesthetic Feelings in Scientific Reasoning

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RESUMEN

Los científicos suelen invocar propiedades estéticas generales, como la elegancia y la simplicidad, a la hora de evaluar sus teorías, pero ¿por qué deberíamos esperar que el placer estético sea señal de un bien epistémico? Defiendo que los juicios estéticos en ciencia se entienden mejor como un caso especial de cognición afectiva, y que los sentimientos en los que se basan estos juicios son los resultados de la supervisión metacognitiva de la calidad de nuestro compromiso con la teoría y la evidencia. Considerar que una teoría es bella indica que encaja bien con nuestros conocimientos previos y que no se ha ajustado artificialmente para acomodar pruebas que de otro modo no la confirmarían ni se ha adaptado al ruido de los datos, lo que convierte el placer estético en una buena heurística para la evaluación de teorías.

PALABRAS CLAVE: *estética en la ciencia, evaluación de teorías, cognición afectiva, meta-cognición, heurística.*

ABSTRACT

Scientists regularly invoke broadly aesthetic properties like elegance and simplicity when evaluating theories, but why should we expect aesthetic pleasure to signal an epistemic good? I argue that aesthetic judgements in science are best understood as a special case of affective cognition, and that the feelings on which these judgements are based are the upshots of metacognitive monitoring of the quality of our engagement with theory and evidence. Finding a theory beautiful fallibly signals that it fits well with our background knowledge and that it's neither artificially adjusted to accommodate otherwise disconfirming evidence nor fitted to noise in the data, which makes aesthetic pleasure a good heuristic for theory evaluation.

KEYWORDS: *Aesthetics in Science, Theory Evaluation, Affective Cognition, Metacognition, Heuristics.*

INTRODUCTION

When evaluating theories, scientists regularly invoke broadly aesthetic properties like elegance, beauty, simplicity, harmony, unity, and a lack of *ad hoc*-ness, gerrymandering, or messiness. The physicist Paul Dirac, for example, said that "the foundations of the theory [of general relativity] are, I believe, stronger than what one could get simply from the sup-

port of experimental evidence. The real foundations come from the great beauty of the theory" [(1980) p. 10]. About the forerunner to plate tectonics, continental drift, the geologist Émile Argand said that "the elegance with which drift theory explains these significant facts, which were not known when the theory was originated, is certainly a strong point in its favour" [quoted in Wegener (1977), p. 131].[1] This suggests that they expect a beautiful theory to be epistemically better than an ugly one, all else being equal. But the fact that scientists rely on aesthetic judgements is one thing; quite another is whether they should do so.

Why would one expect aesthetic satisfaction to signal that we have achieved an epistemic good, whether that be (approximate) truth, knowledge, or even the usefulness of a theory?[2] We are well situated to answer that question if we start from the picture of reasoning and decision-making suggested by recent psychological research, which takes these processes to be tied up with affect and regularly beyond introspective access. If we take this research seriously and also take on board some more speculative ideas about the relationship between aesthetic and metacognitive feelings which I'll present below, then the observed role of aesthetics in science is exactly what we would expect to find. This gives good abductive support for the picture of the relationship between aesthetics and science I'm about to paint. Nevertheless, this paper is programmatic, and details are left for later work.

I outline the role of affect in reasoning in sections I and II before turning to the more speculative part of my account in sections III and IV. I argue that aesthetic considerations are often useful for evaluating scientific theories by drawing on research on metacognition, our capacity for monitoring and controlling ongoing cognitive processes. This is because aesthetic feelings about theories are based on subpersonal metacognitive monitoring that signals the quality of our processing while we engage with the theory and the evidence that bears on it. When we find a theory beautiful, it's a good bet that it fits well with our background knowledge and that it's neither artificially adjusted to accommodate otherwise disconfirming evidence nor fitted to noise in the data, which makes aesthetic pleasure a good but fallible heuristic for the (approximate) truth of a theory. I end (section V) by discussing the reliability of metacognitive feelings, and argue that the moderate reliability of these feelings, as shown by empirical studies, is enough for them to be useful in scientific reasoning.

I. Affect, Cognition, and Subconscious Processing

Psychological research from the past four decades or so has downplayed the distinction between affective and cognitive processing [Moaz and Bar-Haim (2018), Touroutoglou and Barrett (2018), Shackman and Lapate (2018)], after influential philosophical and psychological work from the second half of the last century [e.g., Simon (1967), de Sousa (1987), Damasio (1994), LeDoux (1998)] showed that affective states, generally, and emotions, particularly, are essential to rational decision-making.

Feelings are conscious experiences – canonically, of bodily states like a fluttering heart or a tightness in your throat – whereas emotions can, but need not, be consciously felt. Emotions are richer experiences that "in many cases involve sophisticated cognitive states (including beliefs and desires)" [Arango-Muñoz and Michaelian (2014), p. 9)]. 'Affect' means basically the same as 'feeling'. Its two central components are valence and arousal: affective states range from positive to negative (valence) and from idle to activated (low to high arousal).[3]

As the early research showed, rational and efficient cognition requires well-tuned affect, for example, to signal which problems are worth spending time on and when to stop searching [Reber and Tranel (2018)].[4] This work on the influence of affect on judgement and decision-making prompted a wave of research which resulted in rethinking the role of emotions and subconscious influences on cognition. But talking of affect *influencing* cognition is somewhat misleading, as they are not sharply divided phenomena:

> it appears that such a clear-cut distinction between cognition and emotion is illusive and that most of the relevant processes and conditions involve intricate blends that could be classified as both emotional and cognitive. [Maoz and Bar-Haim (2018), p. 192]

For example, attention and anxiety – exemplars of cognitive and affective phenomena, respectively – can blend together. You can increase someone's anxiety by directing their attention towards a threat and decrease it by directing their attention away from it, and manipulating their levels of anxiety is an indirect way of manipulating their attention [Maoz and Bar-Haim (2018), p.19]. In general, "emotionally salient information enjoys privileged access to working memory" [Okon-Singer et al. (2018), p. 183]. This has consequences not just for attention but for all aspects

of working memory; that is, our "limited-capacity workspace where information is actively maintained, recalled, and manipulated" (*ibid.*), making cognitive and affective phenomena blend together both functionally and phenomenologically. Furthermore, the brain can't be anatomically divided into areas responsible for affect and cognition: "there are no anatomical criteria for deciding which tissue belongs to putative emotion systems or cognitive systems and which does not" and "robust and consistent evidence that a given set of neurons are uniquely emotional or cognitive is lacking" [Touroutoglou and Barrett (2018), p. 192]. Multiple brain regions are involved in both emotional and cognitive processing (e.g., the medial prefrontal cortex and the anterior insula; see Pessoa (2018)).[5] So it's clear that affect and cognition overlap in significant ways. This paper concerns one aspect of this, namely how aesthetic and metacognitive feelings influence scientific reasoning.

Feelings also play a large role in signalling automatic and unconscious processing. "What has become apparent since the second half of the last century is that a large portion of mental processing occurs outside of conscious awareness", as Goldstein and Young say [(2022), p. 345]. A popular framework for making sense of this is dual-process theories [Tversky and Kahneman (1974), Evans (2007)]. The basic idea of dual-process theories is that we have two different modes of processing information,[6] roughly divided into an unconscious, intuitive, fast, and automatic mode with a high capacity (type 1), and a conscious, slow, and analytic mode with a limited capacity (type 2). Much of our cognitive processing is of type 1. As Evans writes, "the great bulk of our everyday cognitive processing is carried out rapidly and implicitly without conscious thought. … Much of our judgement and decision making takes place at this level also" (2007:2). When we are made aware of this processing or its upshots, it's often through feelings. These feelings are central to both modes: for example,

> Positive epistemic feelings, e.g., feelings of familiarity, recognition, agency, ownership, and confidence … signal successful completion for both kinds [types 1 and 2] of problem solving … [and] negative epistemic feelings such as doubt, or frustration are typical of the early stages of canonical Process-2 problem solving. [Fields and Glazebrook (2020), p. 534].

Such feelings play an important role in directing mental processing in general, but for type 1-processing we might not even notice that there was a process going on or that we have reached a decision until one op-

tion or the other *feels* right. These feelings can be first-order (say, you feel that something is off with the data you consider) or metacognitive (you feel confident in your judgement that *p*). Metacognitive feelings[7] play a central role in judgement and decision-making (Ackerman and Thompson (2017)) and are central to how I propose to account for aesthetic considerations in science, so let me say more about them.

II. METACOGNITION

Metacognition is our capacity for monitoring, evaluating, and controlling our ongoing cognitive states or processes.[8] Corresponding to the type 1 and type 2 processes discussed above, we have both automatic (or, procedural) and analytic metacognition [Proust (2013), Shea et al. (2014)]. An example of analytic metacognition is asking yourself whether you have memorised your shopping list (actively probing your memory); an example of automatic metacognition is subconsciously evaluating whether you'll remember it later while writing the list. We're typically made aware of the upshots of automatic metacognition by feelings, for instance by a feeling that you'll remember the items on the list later, or by a nagging doubt. Or consider the tip-of-the-tongue feeling, which is the output of an evaluation of whether you have the relevant information stored: the feeling signals that even though you can't access it at the moment you do have it stored, and therefore that it is worth spending time trying to retrieve it [Dunlosky and Metcalfe (2009)].

Metacognitive evaluation comes into play both in predicting success on a cognitive task and in evaluating whether it was successful. For example, when writing an exam, you'll probably start with a question you feel able to answer. This feeling is a relatively good indicator that you will be successful in the first-order task (here: answering the question) [Dunlosky and Metcalfe (2009), Ch. 4, Fernandez Cruz et al. (2016)]. When writing down your answer to the question, you might experience feelings of error or confidence: this is the output of an evaluation of whether you were successful in that first-order task. This automatic metacognitive monitoring goes on in the background without any conscious effort or control, and we notice it more readily when there is a discrepancy in predicted and incoming information: most of the time we focus on *what* we know, rather than *that* (or whether) we know it.

It's generally accepted that metacognitive judgments are based on subpersonal inferences based on various cues from the processing expe-

rience [Ackerman and Thompson (2017), p. 613]. They can be either cues intrinsic to the object (e.g., the clarity and contrast of a visual figure) or cues extrinsic to it, having to do with how the subject relates to the object (e.g., presentation time and repetition) [Koriat (1997), Mamassian (2022)]. A central cue for metacognition is the *fluency*, or experienced ease, with which one perceives, categorises, computes, or otherwise processes information, with fluency leading to positive affect and disfluency leading to negative affect [Schwarz (2018)]. Other cues include response latency, familiarity, and symmetry.[9]

III. The Metacognitive Account

How does all of this connect to aesthetic appreciation of scientific theories? In a nutshell, the claim is that the feelings that aesthetic judgements are based on are upshots of automatic metacognitive monitoring and evaluation, and that they play a central and often positive role in scientific reasoning. This lets us account for the connection that many scientists believe hold between beauty and truth:[10] by positing an indirect link between them, the central part of which are feelings and the reliability of the metacognitive processes the feelings are based on. Note that I'm only concerned with aesthetic feelings as they arise in scientific or other epistemic contexts, and not with aesthetic feelings in general.

Why focus on feelings? First, aesthetic judgements about theories, like aesthetic judgements in general, are based on feelings. For example, when Cox and Hart claim that the "plate tectonic model explains most of the geologic and geophysical features of trenches and island arcs with elegant simplicity" [(1991), p. 30], this is based on the *experience* of elegance and the delight in the simplicity that elsewhere makes them exclaim about its beauty [(1991), p. 9]. Second, as we have seen, feelings are involved in reasoning, decision-making, and other cognitive processes, so we should expect feelings to also play a central role in scientific reasoning.[11] This doesn't yet account for *aesthetic* feelings: perhaps, say, curiosity, puzzlement, and certainty play an important role whereas feelings of elegance, beauty, and messiness don't. Nothing we've said so far excludes this possibility. However, since we do have a well-supported picture of affective cognition, including the role of metacognitive feelings at all levels of reasoning [Ackerman and Thompson (2017), Fields and Glazebrook (2020)], *and* ample evidence that scientists are often guided by their aesthetic feelings when evaluating theories (e.g., McAllister

(1996)), an explanation of the latter that fits neatly into the former thereby gains some abductive support.

In this section, I'll first present an overview of the account (section III.1.1) before getting into the details (sections III.1.2. and III.1.3). After that, I discuss (section IV) how these feelings can be of heuristic guidance and (section V) empirical evidence on how reliable they are.

III.1. *Aesthetic Feelings as Upshots of Automatic Metacognitive Monitoring*

III.1.1. Overview

The feelings that aesthetic judgements about a theory are based on arise during active engagement with the theory. While you are actively working with it (evaluating it against background knowledge, evaluating the claims of the theory, making interpretive and other decisions, etc.)[12] your mind is also actively engaged in monitoring, evaluating, and controlling your first-order cognition. In other words, parallel to the first-order processing you're engaged in, you're also engaged in a metacognitive monitoring of that first-order processing. The upshot from this metacognitive monitoring is usually signalled as feelings of positive or negative valence. In the case of theory evaluation, the feelings signal, among other things, 1) how well you understand the theory, 2) how well the theory fits your background knowledge, and 3) the internal coherence of the theory. To the extent that these feelings are reliable – and I'll argue that they are reliable enough in section 5 – they thereby give us important evidence about the approximate truth of the theory. To take one example of what specific feelings can signal and how they can play a positive role in scientific reasoning, consider feelings of elegance.[13] They mark the 'sweet spot' between simplicity and fit which signals that we have avoided 'overfitting' the theory to noisy data, and they are plausibly based on effortless fit with background knowledge (more on this below).

III.1.2. Getting into the Details

This account explains aesthetic feelings in theory evaluation as the felt upshots of automatic metacognitive monitoring going on in the background while actively working with the theory. In this respect, my account comes very close to Todd's. Todd (2017) takes the relevant feelings to be of a hybrid 'aesthetic-metacognitive' kind. Todd's is among a handful of metacognitive accounts of aesthetics in science, developed by both psychologists and philosophers. The psychological accounts [Reber (2018), Schwarz (2018)] are too narrow, concerning only the role of flu-

ency in judgments of beauty and of truth. Aesthetic judgments go beyond judgments of beauty (and epistemic evaluations go beyond judgments of truth) and they are based on more than fluency.[14] Arcangeli and Dokic (2020) widen the scope somewhat by also discussing disfluency and sublimity. However, like Todd (2017), they neither focus on the active engagement with the theory and the evidence that bears on it in producing the metacognitive feelings nor on the reliability of these feelings, both of which are central to explaining how aesthetic feelings *qua* metacognitive feelings can be of use in scientific reasoning. Metacognitive feelings arise out of ongoing cognitive effort, including the initial search for whether it's worth trying to perform a given cognitive task. The aesthetic appreciation that may be expressed by saying that a theory is, say, elegant or beautiful is similarly a felt response to how the scientist plays around with the theory in her mind, testing how it can explain what it purports to explain, considering how it fits with background beliefs, what happens if she tweaks it this or that way, or otherwise actively engages with it.

The aesthetic experience is in part a response to the effortlessness (fluency) with which we can make sense of the theory and make sense of the world through the theory.[15] Much like how the effortlessness of conversing in your mother tongue signals how easily you understand what's being said, so fluency while working with a theory signals that you understand it well. *Ceteris paribus*, this puts you in a good position to judge whether the theory is true.

Metacognitive monitoring leads to more flexible and accurate behaviour and is useful to the extent that it helps us navigate the world. We want to know whether the theory is (approximately) true of the world – whether the world is (roughly) as the theory says it is – and even when we focus on its intrinsic properties such as its simplicity, we usually have our eyes firmly fixed on the world. To illustrate with a simple case, consider that when you feel certain that, say, 67+12=79, your focus is on the correctness of this equation, but your certainty is a response to how effortlessly you recognise that it's correct. Similarly, your aesthetic feelings are about what the theory says even when they arise largely as a response to how effortlessly you can work with it. Automatic metacognition and other type 1 processes going on in the background while you are working with the theory give rise to what is experienced as aesthetic feelings. They are like the score presented to your conscious mind by your evaluation of the theory and might be the only consciously available upshots from those processes. The (mostly automatic) inferences from cues that metacognition is based on utilise learned regularities between cues, con-

texts, and outcomes (e.g., whether you in fact remember *p* later, whether it turned out to be true, etc.), which is why they tend to be helpful. Roughly, positively valenced feelings which arise in the scientist when she works with the theory are like 'thumbs up' signals from the subconscious monitoring going on in the background, signalling that everything flows smoothly and that no problem has been detected. Negative feelings, on the other hand, signal that something is not working properly, that there is a problem somewhere needing further investigation. It is a signal that something goes awry when trying to use the theory to explain, predict, or otherwise gain insight into a phenomenon.[16]

I said that the feelings might be the only consciously available upshots from the automatic processes. This is important because we sometimes make more accurate judgements when they are based on implicit inferences from ongoing experience (i.e., online processing) rather than our explicit beliefs. For instance, Koriat and colleagues (2009) found that we make more correct judgements of learning when they are based on cues arising while actively engaging in the task than when predicting others' future recall without simultaneously engaging in a similar task (and therefore not being able to draw on metacognitive cues from the processing experience).

Moving on, why should we believe that aesthetic feelings are generated by metacognition? One reason is the striking similarity between aesthetic feelings in science and typical metacognitive feelings. Think, for instance, about the pleasure and satisfaction you experience when you finally 'get' an account you've been struggling with or the immediate aversion you feel if it generates a paradox. The epistemic evaluation is signalled by feelings that look more at home in typical aesthetic contexts. Typical aesthetic and metacognitive feelings – to the extent that they can be sharply separated – often appear together and, in some cases, aesthetic feelings only appear in favourable epistemic circumstances. Understanding, for example, is sometimes necessary for aesthetic appreciation, most notably in mathematics [Zeki et al. (2014)] and in modern art. Furthermore, both metacognitive feelings like confidence, feelings of knowing, etc., and aesthetic feelings like feelings of beauty, elegance, and milder liking are often based on the same cues [Schwarz (2018)]. To take a well-worn example, fluency is one of the main cues utilised in metacognitive monitoring and seems to play a similar role in aesthetic judgements. We generally perceive something as more aesthetically pleasing when fluently processed. We also believe that we have seen it before, that it is true, and that we're more likely to remember if later if it was flu-

ently processed [Schwarz (2018), Reber (2018), Alter and Oppenheimer (2009)]. We also have an easier time understanding the content if it's presented in a form conducive to fluency [Reber et al. (2004)].

Furthermore, the content of the feelings varies with the context, and on the present model whether they are experienced as metacognitive or aesthetic similarly depends on context [see also Todd (2017), p. 229, Arcangeli and Dokic (2020), pp. 115–6]. For example, fluency consistently impacts judgements across judgements of learning [Koriat (2008), Undorf et al. (2017)], judgments of truth [Dechêne et al. (2010)], mode of processing [Thompson et al. (2013)], and confidence [Ackerman and Zalmanov (2012)]. The basis for the feeling is the same but it's taken to convey different information depending on the task at hand. We don't confuse whether we think something is true, stored in memory, or whether we'll remember it later, even when these judgements are made in a split second and based mainly on the effortlessness of reaching the judgement.[17] The feeling is interpreted in each situation as conveying relevant and fine-grained information, but exactly what this information is varies enormously depending on context (in particular, what the object of attention is; e.g., a question or a claim's truth-value). The further claim that these feelings sometimes take on a distinct *aesthetic* flavour is not yet supported by empirical evidence, though it is suggested by the above-mentioned reasons and would explain the curiously close connections between aesthetic and epistemic judgements in science (Todd (2008)).

III.1.3. Elegance and Effortless Fit

That aesthetic feelings can be exploited to great effect can be seen from the way they alert us to the dangers of overfitting and *ad hoc*-ness. Feelings of elegance and other kinds of beauty can alert us to the fact that the parts of the theory fit snugly together, which in turn is an indicator that we have neither artificially adjusted the theory to fit the data with some *ad hoc* hypotheses nor 'overfitted' it by adjusting it to fit all data points, thus making it likely that it fits noise as well as signal. 'Overfitting' refers to the somewhat puzzling phenomenon that if we try to describe the trend in a dataset by fitting a curve to the data points, then a curve that fits all the data often fits *new* data less well than a more approximately fitted curve does. A simple, smooth curve better captures the trend and therefore makes better predictions about where future data points will fall.

The reason why a simpler curve is more likely to accurately reflect the true trend behind the data seems to be that such a curve is less likely

to be fitted to errors in the data; a complex curve is fitted to both signal and noise (Forster and Sober (1994)). Something like overfitting can occur beyond curve-fitting when epicycles are added to a theory to fit all the (non-qualitative) data [Williamson (2016)]. An *ad hoc* theory contains hypotheses which lack independent support (typically included only to save the theory from refutation, or containing parameters which need to be fixed in light of the evidence for that evidence to bear on the theory) and theoretical unity (there's no underlying connection between the claims) [Schindler (2018)]. Neither overfitted nor *ad hoc* theories get the fit quite right: there's either a tension or a lack of cohesiveness to the theory that we find unpleasantly messy.

Despite the dangers of overfitting, the best indicator of a theory's truth is that it fits the evidence, in the form of both experimental and observational data and our best theories (or other background knowledge).[18] Sometimes an evaluation of fit with evidence happens at the periphery of your attention while you focus on some first-order task, like deriving a prediction from the theory or using it to explain some phenomenon, and it's plausibly felt as high or low confidence in whatever is the focus of your attention. If this is right, there should be a positive correlation between confidence and discovered fit between items: the worse the fit you detect is, the lower your confidence will be, and the better the detected fit is the higher your confidence will be.

Koriat's (e.g., 2012) prominent 'self-consistency model' of confidence suggests that this is so. Confidence is based on cues from the decision-making, like how much deliberation it took to reach the decision and how quickly you reached it, and Koriat takes the main cue for confidence to be 'self-consistency', or the consistency of one's evidence in favour of a given option. When most of the evidence supports one option, that's the one you choose, and the bigger the majority, the more confident you will be in your choice. To put it differently, the more items that fit together, the more confident you'll be.[19]

Humans (and other animals) are extremely sensitive to harmony, or to things fitting together in a unified whole where the inclusion and arrangement of the parts make sense, and nothing sticks out. This sensitivity is both pleasurable and useful, for example in pattern recognition. Consider how much easier it is to understand and remember a narrative than a random list: an elegantly unified theory is like a narrative where the elements are interrelated whereas a disunified theory is like a list of unrelated elements. The tighter coherence constraints in a narrative make it easier to notice an element that doesn't fit in a narrative than in a list;

the narrative's structure binds everything in place at multiple points, making dangling loose ends stand out.

For these feelings to carry information about the fit between theory and evidence, both the evidence and the theory must be represented in your global workspace (roughly, working memory). This, in turn, explains why the same feelings carry information only about the internal coherence[20] of a theory when viewed in isolation from the evidence: you experience the same pleasurable detection of fit between represented items, but since only the theory itself is represented, the feelings signal that elements of the theory fit neatly together but not that it fits the evidence. This also explains what goes on when you find a theory beautiful but unlikely to be true: you see that everything *internal* to the theory fits together perfectly. Isolated from the disconfirming evidence the theory is so beautiful that it's almost a shame that you have to consider that evidence; when you do so you notice the conflict between what the theory says and what you know independently to be the case, and the result is no more pleasant than the overall impression of a pretty picture in an ugly frame.[21]

Are we forced to conclude that positive aesthetic feelings signal *both* fit and lack of fit (i.e., that it avoids overfitting)? No, not if we look at how certain feelings can signal a good *overall* fit. Consider elegance. A promising hypothesis which isn't empirically tested yet but squares well with historical cases[22] is that the experience of effortless (i.e., fluent) fit when working with a theory gives rise to feelings of elegance.[23] The effortless fit signalled by these feelings need not (and often will not) be *a perfect* fit but rather that the overall picture makes good sense. Elegance marks the 'sweet spot' between simplicity and fit which signals that we have avoided overfitting the theory to noisy data without sacrificing overall fit. Take, for example, the Vine-Matthews-Morley hypothesis (VMM), which is a central part of the theory of plate tectonics and is regularly described as elegant. VMM says that the 'zebra pattern' of normally and reversely magnetised rock parallel to midocean ridges is caused by magnetisation fossilised in the cooling magma of newly minted seafloor as the polarity of the earth's magnetic field changes. The hypothesis was independently proposed by Vine and Matthews, on the one hand, and Morley, on the other, and both teams were guided by their sense of elegance – and of a *good enough* fit. Vine is unusually open about being guided by aesthetic considerations, for instance in describing his early acceptance of continental drift: "I decided it had to be true; it was too simple and elegant" [in Frankel (1982), p. 12]. Morley said that VMM was

"like finding the key piece to an enormous jigsaw puzzle that made everything fit together" [(2003) p. 83], and Mason, who collected much of the magnetic data, connects his immediate acceptance of the hypothesis to its elegance, saying that it "offered an elegant explanation … I had absolutely no doubt as to the correctness of their hypothesis" [(2003), p. 41].

The pleasure these scientists felt when engaging with this hypothesis, based on the way it fitted together different ideas in a mutually supportive framework and the elegance of the ensuing explanation of the magnetic lineations, also made them confident in it.[24] Strikingly, the scientists rejected what didn't fit neatly with their explanation (for example, data on so-called self-reversing rocks, which cast serious doubt on the hypothesis of geomagnetic reversals, and old rocks found near midocean ridges which conflicted with the hypothesis of seafloor spreading). As Hess, who developed the seafloor spreading hypothesis that VMM relies on, said about the apparently contradicting data, "if these are disregarded everything fits just as it should" [in Frankel (1982), p. 36]. If they had set aesthetic considerations to one side and taken all the data into account, they would have fallen prey to overfitting (and ended up with a less predictively successful hypothesis), for the apparently contradicting data turned out to be misleading. Instead, they let their sense of elegance steer them to the hypothesis that achieved a 'Goldilocks' balance between a simple, streamlined picture and a good fit with the data.

If we accept that the aesthetic feelings relevant to scientific reasoning are metacognitive, we're still faced with the question of how they can be useful for theory evaluation. I address this next.

IV. Heuristic Guidance

As Breitenbach (2013) argues, an explanation of the role of aesthetic considerations in theory evaluation must account for "the apparent instability of the link between the beauty of the theory and its truth" [(2013), p. 83]. There are too many cases of beautiful theories turning out to be false (e. g., Copernicus' model of beautifully circular planetary orbits) and of ugly theories that are approximately true (e. g., the standard model in physics) for it to be plausible that there is a direct link between beauty and truth [Ivanova (2020), p. 95]. But we still need to account for the fact that beautiful theories quite often turn out to be approximately true (e.g., general relativity, the Vine-Matthews-Morley hypothesis). What we need is an *indirect* link between beauty and truth.

Both Ivanova (2020) and Breitenbach (2013) take aesthetic appreciation to be indicative of understanding instead of truth. For understanding to be a real alternative it must (unlike knowledge) be non-factive, i.e., not entail truth. However, even self-proclaimed non-factive accounts of understanding require truth: for example, Potochnik says "[a] posit is epistemically acceptable when its divergence from truth is insignificant" [(2017), p. 100] and Elgin says "[t]o accept that *p* … is to take it that *p*'s diversions from truth, if any, is negligible" [(2019), p. 390]. Sliwa (2015), furthermore, gives a strong argument against (genuinely) non-factive accounts of understanding. Instead of going into the debate on understanding here, I'll provide an alternative.

If not non-factive understanding, what can give us the required indirect link between beauty and truth? Heuristics can.

Heuristics are rules of thumb or fast-and-frugal cognitive strategies that usually consist of simplifying a problem or ignoring some information so that a decision can be reached with minimal effort [Tversky and Kahneman (1974), Gigerenzer (2007)]. A well-known example is the availability heuristic, by which people judge that the answer that first comes to mind (the easiest available option) is the right one, or that the example that first comes to mind is representative of its category. The availability of an example is not taken as a necessary or sufficient condition for the representativeness of the example. Instead, judgements that an example is representative are made in accordance with the (fallible and defeasible) rule of thumb that if an example is easily available, then it is representative. That we act in accordance with such rules is typically not available for introspection but discovered through experiments and theorising: something like the availability heuristic best explains our behaviour, but 'from the inside' it just feels like we have come up with the right answer. Heuristics are useful, but fallible, and require a favourable environment to work well [Gigerenzer (2007)].

Longino [e.g., (2008)] has argued that theoretical virtues – including aesthetic ones – are heuristics that guide research despite not being indicative of truth [(2008), p. 74]. But we can easily combine the claim that aesthetic virtues are indicative of truth with the claim that scientists rely on aesthetic feelings as a heuristic for assessing theories.

Just as with the availability heuristic, the aesthetic appeal of a theory isn't taken as a criterion for thinking that the theory is true: being, say, elegant is not a necessary and certainly not a sufficient condition for truth. Instead, judgements that a theory is true are made in accordance with

the rule of thumb that if it's elegant, then it is probably true, again taking it to be a fallible and typically unconsciously applied cognitive shortcut.

This is similar to Arcangeli and Dokic's (2020). Drawing on fluency-based accounts of beauty, they argue that scientists have implicitly learnt that fluency connects judgements of beauty and truth and are using that as a heuristic in theory evaluation. "The point of the heuristic is to *extend* one's ability to form judgements of truth" [(2020, p. 116] by relying on judgements of beauty as a shortcut. I don't think the best interpretation of heuristics is as an extension of one's ability to make judgements, but as an acknowledgement of the *fallibility* of the rule. As noted above, heuristics are at best generally useful, but even in favourable circumstances they can lead us astray. This fits the historical data that beauty relatively often points towards truth (e.g., in Gell-Mann's prediction of the omega-minus particle, the development of the Vine-Matthews-Morley hypothesis, and the development of the double helix model of DNA: see also Glynn (2010), Chandrasekhar (1987), McAllister (1996), Strevens (2020), and Ivanova (2020)).

To sum up, when working with or explicitly evaluating theories, metacognitive monitoring gives rise to feelings which are used as heuristics for theory evaluation. The aesthetic feelings may be the only consciously available upshots from this monitoring. Importantly, such evaluations are normally made against a background of empirical evidence, evidence which must fit together with what the theory says to elicit positive aesthetic feelings.[25] Unless you are bracketing off background knowledge and consider the theory purely for its own sake, aesthetic pleasure is – defeasible and fallibly – indicative of empirical fit.

V. Reliability

If relying on such feelings is a heuristic for theory choice, then we need to ask whether this heuristic is reliable enough as a guide to true theories to justify scientists' use of it. To some extent that has already been answered: if it helps us avoid the dangers of overfitting, *ad hoc*-ness, and a poor fit with background knowledge, then we are better off relying on it. This is further supported by studies on how accurate metacognitive feelings are about their target states and processes, which I discuss in this last section.[26]

These studies have mixed results but generally point towards a moderate to high level of reliability. For example, Fernandez Cruz, Arango-

Muñoz, and Volz (2016) looked at feelings of error during mental calculations and found that they were positively correlated with arithmetic errors. The participants were successful in almost 90% of the trials by either reporting a feeling of error when they committed a calculation error or by *not* reporting a feeling of error when everything went well [(2016), p. 115]. In other words, the *feelings* of error were good indicators of *actual* error, and low or absent feelings of error were good indicators that everything went well. Boldt, de Gardelle, and Yeung (2017) found that confidence in perceptual tasks was positively correlated with correctness. When the participants expressed high confidence they gave very few incorrect answers, and when they expressed low confidence, they gave many incorrect answers. This did not just hold for the 'certainly wrong' and 'certainly correct' judgements: there was a monotonic decrease in error rates with the level of confidence [(2017), p. 1525]. Similar results are found for many other cognitive tasks and metacognitive feelings [e.g., Koriat (2008), (2012), Reder (1987), (1996), Schwartz (1994), Yeung and Summerfield (2012)).

We are, however, also susceptible to biases, like overconfidence [Griffin and Tversky (1992)], the hard-easy effect (being overconfident about difficult things and underconfident about what's easy; see Koriat et al. (2009)), and the illusion of truth-effect (mistaking something being fluently processed for it being true; see Dechêne et al. (2010)), which lowers the reliability of metacognition. Relying on aesthetic feelings is like other heuristics in that it's often useful and, in many circumstances, more useful than complex decision strategies, but sometimes they lead us seriously astray.[27] This fits well with the riskiness of relying on aesthetic judgements in science. Consider pre-modern natural philosophy, where delight in symmetry and simplicity led to spectacularly wrong theories, like Paracelsus' (1439–1541) 'explanatory' analogies between metals, human organs, and stars and planets or Newton's alchemy [Strevens (2020), p. 212], both guided by the idea that there must be a simple, elegant pattern underlying all the world's disparity. Hossenfelder (2018) argues that contemporary particle physics is likewise blinded by aesthetic considerations. Whether Hossenfelder is right or not, the historical track record shows that aesthetic sensibilities sometimes leads towards and at other times away from truth [Ivanova (2020), p. 95] – also in modern theories, like with Einstein and Fred Hoyle's aesthetic distaste of Big Bang, which led Einstein to postulate the cosmological constant and Hoyle to develop the steady-state theory to avoid the displeasing temporal asymmetry [Hossenfelder (2018) pp. 29-30]. This makes sense if the reliance on aes-

thetic feelings is a heuristic, where what we'd expect is that the feelings tend to be useful but can also be a hindrance.

In sum, we should be carefully optimistic about the usefulness of aesthetic feelings for scientific reasoning: the feelings, *qua* upshots of metacognitive monitoring, give us valuable information about our cognitive performance and how well the evaluated theory and evidence fit together and so, indirectly, about how good the theory is. If we follow our aesthetic preferences, we stand a better chance of hitting upon a true theory because our aesthetic pleasure signals that the theory fits well with our background knowledge and is neither artificially adjusted to accommodate disconfirming evidence nor overfitted to accommodate noise in the data. As this account is about the psychology of theory evaluation, it's an empirical question whether it correctly describes scientific reasoning and whether these feelings are reliable enough to positively influence theory choice, but it gives us a promising starting point for explaining *why* aesthetic pleasure is so useful for discovering good theories. If the picture presented here is on the right track, then aesthetic feelings concerning scientific theories inherit their usefulness from the metacognitive processes that these aesthetic feelings are based on, which takes us one important step closer to explaining the role that aesthetic considerations play in scientific reasoning.[28]

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NOTES

[1] Similar quotes by Kepler, Poincaré, Einstein, Darwin, Weyl, Heisenberg, Duhem, Polkinghorne, and Mach, among others, can be found in, e.g., Chandrasekhar (1987), Todd (2008), Breitenbach (2013), Osborne (1984), and McAllister (1996).

[2] For present purposes, we can think of theories *qua* objects of aesthetic evaluation as truth-apt representations of how the world is.

[3] I'll sometimes talk about 'affective states' in general as encompassing emotions, but never the other way around.

[4] See Damasio (1994), p. 193, for an amusing example of how badly cognition is affected by emotional impairment.

[5] See also Okon-Singer et al.: "the impact of emotion on attention reflects the coordinated activity of multiple cortical and subcortical brain regions" [(2018), p. 182].

[6] These theories are divided into dual *process* and dual *system* theories: the former makes a distinction between two modes of processing, the latter between two different cognitive systems underlying such processing. The difference isn't important for our purposes.

[7] Also called 'epistemic' or 'noetic' feelings.

[8] For variations on this definition, see Ackerman and Thompson (2017), p. 607), Proust (2013), p. 4), and Shea et al. (2014), p. 186.

[9] These cues, and many others besides, tend to affect the fluency of the task.

[10] Recall the quotes given in the introduction.

[11] In the recent literature on aesthetics in scientific theory evaluation there is a strong trend towards focusing on the psychology of theory evaluation, though not so much on feelings in particular: see Kuipers (2002), Breitenbach (2013), Todd (2017), Reber (2018), Schwarz (2018), Ivanova (2020), Arcangeli and Dokic (2020), Bird (2020). Some of these accounts also focus on metacognitive feelings – more on them below.

[12] All of which can be done both deliberately and automatically.

[13] Here I take elegance to be one of the many ways something can be beautiful.

[14] See Cochrane (2021) and Armstrong and Detweiler-Bedwell (2008) for convincing criticisms of fluency-based accounts' ability to explain everything there is to beauty (not to mention other aesthetic categories).

[15] This focus on processing fluency is shared by all metacognitive accounts, though we differ in how central this one cue is taken to be. I don't take fluency to be a necessary or sufficient condition for aesthetic experience, although it often has a role to play in it. See Schwarz (2018) for a good overview of the empirical literature.

[16] Shouldn't it be equally pleasurable to understand that a theory is wrong? That doesn't seem to be the case, presumably because noticing that it's wrong involves noticing that what the theory says contradicts other things you know to be the case, and feelings of elegance, harmony, and beauty standardly involve items fitting together into a cohesive whole. (We come back to this below.)

[17] This point shouldn't be confused with misattributions of the feeling's source, like when a teacher thinks a student's essay is bad because of the disfluent experience of reading their ugly handwriting.

[18] Of course, we might be wrong about what we think we know. Copernicus' heliocentric theory of the solar system did not fit with the background beliefs of Aristotelian physics and Christian theology. That did not show that the elements of his theory which contradicted the accepted beliefs were wrong; it showed that those accepted beliefs did not amount to knowledge.

[19] See Todd (2017), pp. 79–80, for a discussion of *feelings* of fit as a variant of feelings of understanding.

[20] I.e., the consistency between the claims the theory makes.

[21] An example of a theory that was judged favorably when looked at in isolation from a good chunk of the evidence is found in Wegener's discussion of contraction theory. After arguing that it was false, he said apologetically that it had been "applied to a large number of individual research results with such consistency that even today it possesses a degree of attractiveness, with its bold simplicity of concept and wide diversity of application" (1977), p. 30). Its 'boldness' of its simplicity and wideness of scope lent it an attractiveness that not even its falsity could undo, suggesting that when it was viewed in isolation from the disconfirming evidence it was very attractive indeed.

[22] See below.

[23] Incidentally, in a series of studies Menninghaus and colleagues found that people explicitly associate elegance with fluency [(2019), p. 5].

[24] Paul Dirac wrote that "one has a great confidence in [a] theory arising from its great beauty, quite independently of its detailed successes" [(1980), p. 40], quoted in Ivanova [(2020), p. 88]. That's an extreme case, but it shows what can otherwise be harder to spot, namely that the pleasure of seeing how everything fits perfectly together – a typical aesthetic delight – is closely connected to acceptance through its influence on confidence.

[25] Normally, that is, in sciences relying on empirical evidence; this is less relevant for mathematics and theoretical physics.

[26] Philosophical (not psychological) metacognitive accounts have been surprisingly unconcerned with the reliability of these feelings (though Todd (2020), p. 78 and (2017), pp. 223–4, comments on it).

[27] An important question that must be answered in future work is what the difference is between circumstances when aesthetic pleasure is indicative of truth and when it's not.

[28] Thanks to Timothy Williamson, Nicholas Shea, Boaz Laan, and an anonymous referee for *Teorema* for comments on earlier drafts.

REFERENCES

ACKERMAN, R. and ZALMANOV, H. (2012), "The Persistence of the Fluency-Confidence Association in Problem-Solving"; *Psychonomic Bulletin & Review*, 19, pp. 1187–92.

ACKERMAN, R. and THOMPSON, V. (2017), "Meta-Reasoning: Monitoring and Control of Thinking and Reasoning"; *Trends in Cognitive Sciences*, 21, 8, pp. 607–17.

ARANGO-MUÑOZ, S. and MICHAELIAN, K. (2014), "Epistemic Feelings, Epistemic Emotions: Review and Introduction to the Focus Section"; *Philosophical Inquiries*, 2, pp. 97–122.

ARCANGELI, M. and DOKIC, J. (2020), "A Plea for the Sublime in Science"; pp. 104–24, in M. Ivanova and S. French (eds.) *The Aesthetics of Science: Beauty, Imagination and Understanding*. New York and Abingdon: Routledge.

ARMSTRONG, T. and DETWEILER-BEDELL, B. (2008), "Beauty as an Emotion: The Exhilarating Prospect of Mastering a Challenging World"; *Review of General Psychology*, 12, 4, pp. 305–29.

BOLDT, A., DE GARDELLE, V. and YEUNG, N. (2017), "The Impact of Evidence Reliability on Sensitivity and Bias in Decision Confidence"; *Journal of Experimental Psychology: Human Perception and Performance*, 43, 8, pp. 1520–31.

BREITENBACH, A. (2013), "Aesthetics in Science: A Kantian Proposal"; *Proceedings of the Aristotelian Society*, 113, 1, pp. 83–100.

CHANDRASEKHAR, S. (1987), *Truth and Beauty: Aesthetics and Motivations in Science*; University of Chicago Press.

COCHRANE, T. (2021), *The Aesthetic Value of the World*; Oxford: Oxford University Press.

COX, A. and HART, R. B. (1991), *Plate Tectonics: How it Works*; Blackwell Scientific Publications: John Wiley & Sons, Inc.

DAMASIO, A. (1994), *Descartes' Error: Emotion, Reason and the Human Brain*; London: Vintage Books.

DECHÊNE, A., STAHL, C., HANSEN, J. and WÄNKE, M. (2010), "The Truth About the Truth: A Meta-Analytic Review of the Truth Effect"; *Personality and Social Psychology Review*, 14, 2, pp. 238–57.

DE SOUSA, R. (1987), *The Rationality of Emotion*; Cambridge and London: The MIT Press.

DIRAC, P. A. M. (1980), "Why We Believe in the Einstein Theory"; pp. 1–11, in B. Gruber and R. S. Millman (eds.), *Symmetries in Science*. New York and London: Plenum Press.

DUNLOSKY J. and METCALFE, J. (2009), *Metacognition*; California: SAGE publications, Inc.

ELGIN, C. (2019), "True Enough"; pp. 384–98, in D. Edwards (ed.) *Truth: A Contemporary Reader*. London and New York: Bloomsbury.

EVANS, J. St. B. T. (2007), *Hypothetical Thinking: Dual Processes in Reasoning and Judgement*; Hove and New York: Psychology Press.

FERNANDEZ CRUZ, A. L., ARANGO-MUÑOZ, S., and VOLZ, K. (2016), "Oops, Scratch That! Monitoring One's Own Errors During Mental Calculation"; *Cognition*, 146, 110–20.

FORSTER, M. and SOBER, E. (1994), "How to Tell When Simpler, More Unified, or Less *Ad Hoc* Theories Will Provide More Accurate Predictions"; *British Journal for the Philosophy of Science*, 45, pp. 1–35.

FRANKEL, H. R. (1982), "The Development, Reception, and Acceptance of the Vine-Matthews-Morley Hypothesis"; *Historical Studies in the Physical Sciences,* 13, 1, pp. 1–39.

GIGERENZER, G. (2007), *Gut Feelings: The Intelligence of the Unconscious*; New York: Viking Penguin.

GOLDSTEIN, A. and YOUNG, B. D. (2022), "The Unconscious Mind"; pp. 344–63, in B. D. Young and C. D. Jennings (eds.) *Mind, Cognition, and Neuroscience: A Philosophical Introduction*. New York and London: Routledge.

GRIFFIN, D. and TVERSKY, A. (1992), "The Weighing of Evidence and the Determinants of Confidence"; *Cognitive Psychology*, 24, pp. 411–35.

HOSSENFELDER, S. (2018), *Lost in Math: How Beauty Leads Physics Astray*; New York: Basic Books.

IVANOVA, M. (2020), "Beauty, Truth and Understanding"; pp. 86–103, in M. Ivanova and S. French (eds.) *The Aesthetics of Science: Beauty, Imagination and Understanding*. New York and Abingdon: Routledge.

LEDOUX, J. (1998), *The Emotional Brain: The Mysterious Underpinnings of Emotional Life*; London: Phoenix.

LONGINO, H. E. (2008), "Values, Heuristics, and the Politics of Knowledge"; pp. 68–86, in M. Carrier, D. Howard, and J. Kourany (eds.) *The Challenge of the Social and the Pressure of Practice: Science and Values Revisited*. University of Pittsburgh Press.

KORIAT, A. (1997), "Monitoring One's Own Knowledge During Study: A Cue-Utilization Approach to Judgements of Learning"; *Journal of Experimental Psychology: General*, 126, 4, pp. 349–70.

— (2008), "Easy Comes, Easy Goes? The Link Between Learning and Remembering and its Exploitation in Metacognition"; *Memory & Cognition*, 36, pp. 416–28.

— (2012), "The Subjective Confidence in One's Knowledge and Judgements: Some Meta-Theoretical Considerations"; pp. 213–33, in M. J. Beran, J. Brandl, J. Perner, and J. Proust, (eds.) *Foundations of Metacognition*. Oxford: Oxford University Press.

KORIAT, A, ACKERMAN, R., LOCKL, K., and SCHNEIDER, W. (2009), "The Memorizing Effort Heuristic in Judgments of Learning: A Developmental Perspective"; *Journal of Experimental Child Psychology*, 102, pp. 265–79.

MAOZ, K. and Bar-Haim, Y. (2018), "Thoughts on Cognition-Emotion Interactions and Their Role in the Diagnosis and Treatment of Psychopathology"; pp. 189–92, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) (2018), *The Nature of Emotion: Fundamental Questions*; 2nd ed. Oxford: Oxford University Press.

MASON, R. (2003), "Stripes on the Sea Floor"; pp. 31–45, in N. Oreskes (ed.) *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Colorado: Westview Press.

MCALLISTER, J. (1996), *Beauty and Revolution in Science*; New York: Cornell University Press.

MENNINGHAUS, W., WAGNER, V., KEGEL, V., KNOOP, C. A., and SCHLOTZ, W. (2019), "Beauty, Elegance, Grace, and Sexiness Compared"; *PLoS ONE*, 14, 6, e0218728, pp. 1–19.

MORLEY, L. W. (2003), "The Zebra Pattern"; pp. 67–85, in N. Oreskes (ed.) *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Colorado: Westview Press.

OKON-SINGER, H., STOUT, D. M., STOCKBRIDGE, M. D., GAMER, M., FOX, A. S., and SHACKMAN, A. J. (2018), "The Interplay of Emotion and Cognition"; pp. 181–5, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) *The Nature of Emotion: Fundamental Questions*. 2nd ed. Oxford: Oxford University Press.

OSBORNE, H. (1984), "Mathematical Beauty and Physical Science"; *British Journal of Aesthetics*, 24, 4, pp. 291–300.

PESSOA, L. (2018), "The Cognitive-Emotional Brain"; pp. 202–6, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) *The Nature of Emotion: Fundamental Questions*. 2nd ed. Oxford: Oxford University Press.

POTOCHNIK, A. (2017), *Idealisation and the Aims of Science*; Chicago: University of Chicago Press.

PROUST, J. (2013), *The Philosophy of Metacognition: Mental Agency and Self-Awareness*; Oxford: Oxford University Press.

REBER, J. and TRANEL, D. (2018), "Emotions Are Important for Advantageous Decision-Making"; pp. 359–65, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) *The Nature of Emotion: Fundamental Questions*. 2nd ed. Oxford: Oxford University Press.

REBER, R. (2018), "Beauty and Truth in Mathematics: Evidence from Cognitive Psychology"; pp. 252–67, in S. Bangu (ed.) *Naturalizing Logico-Mathematical Knowledge: Approaches from Philosophy, Psychology and Cognitive Science*. New York and Abingdon: Routledge.

REDER, L. M. (1987), 'Strategy Selection in Question Answering'; *Cognitive Psychology*, 19, pp. 90–138.

— (1996) *Implicit Memory and Metacognition*; Mahwah, N.J.: Erlbaum.

SCHINDLER, S. (2018), *Theoretical Virtues in Science: Uncovering Reality Through Theory*; Cambridge: Cambridge University Press.

SCHWARTZ, B. (1994), "Sources of Information in Meta-Memory: Judgements of Learning and Feelings of Knowing"; *Psychonomic Bulletin & Review*, 1, 3, pp. 357–75.

SCHWARZ, N. (2018), "Of Fluency, Beauty, and Truth: Inferences from Metacognitive Experiences"; pp. 25–46, in J. Proust and M. Fortier (eds.) *Metacognitive Diversity: An Interdisciplinary Approach*. Oxford: Oxford University Press.

SHACKMAN, A. J. and LAPATE, R. C. (2018), "Afterword: How Do Emotion and Cognition Interact?"; pp. 209–11, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) *The Nature of Emotion: Fundamental Questions*. 2nd ed. Oxford: Oxford University Press.

SHEA, N., BOLDT, A., BANG, D., YEUNG, N., HEYES, C., and FRITH, C. D. (2014), "Supra-Personal Cognitive Control and Metacognition"; *Trends in Cognitive Sciences*, 18, 4, pp. 186–93.

SIMON, H. A. (1967), "Motivational and Emotional Controls of Cognition"; *Psychological Review*, 74, 1, pp. 29–39.

SLIWA, P. (2015), "Understanding and Knowing"; *Proceedings of the Aristotelian Society*, CXV, part 1, pp. 57–74.

STREVENS, M. (2020), *The Knowledge Machine: How Irrationality Created Modern Science*; New York: Liveright Publishing Corporation.

THOMPSON, V. A., TURNER, J. A. P., PENNYCOOK, G., BALL, L. J., BRACK, H., OPIR, Y. and ACKERMAN, R. (2013), "The Role of Answer Fluency and Perceptual Fluency as Metacognitive Cues for Initiating Analytic Thinking"; *Cognition*, 128, pp. 237–51.

TODD, C. (2008), "Unmasking the Truth Beneath the Beauty: Why the Supposed Aesthetic Judgements Made in Science May Not Be Aesthetic at All"; *International Studies in the Philosophy of Science*, 22, 1, pp. 61–79.

— (2017), "Fitting Feelings and Elegant Proofs: On the Psychology of Aesthetic Evaluation in Mathematics"; *Philosophia Mathematica*, 26, 2, pp. 211–33.

— (2020), "Imagination, Feelings, and Reasoning"; pp. 63–85, in M. Ivanova and S. French (eds.), *The Aesthetics of Science: Beauty, Imagination and Understanding*. New York and Abingdon: Routledge.

TOUROUTOGLOU, A. and FELDMAN BARRETT, L. (2018), "Beyond Cognition and Emotion"; pp. 192–6, in A. S. Fox, R. C. Lapate, A. J. Shackman, and R. D. Davidson (eds.) *The Nature of Emotion: Fundamental Questions*. 2nd ed. Oxford: Oxford University Press.

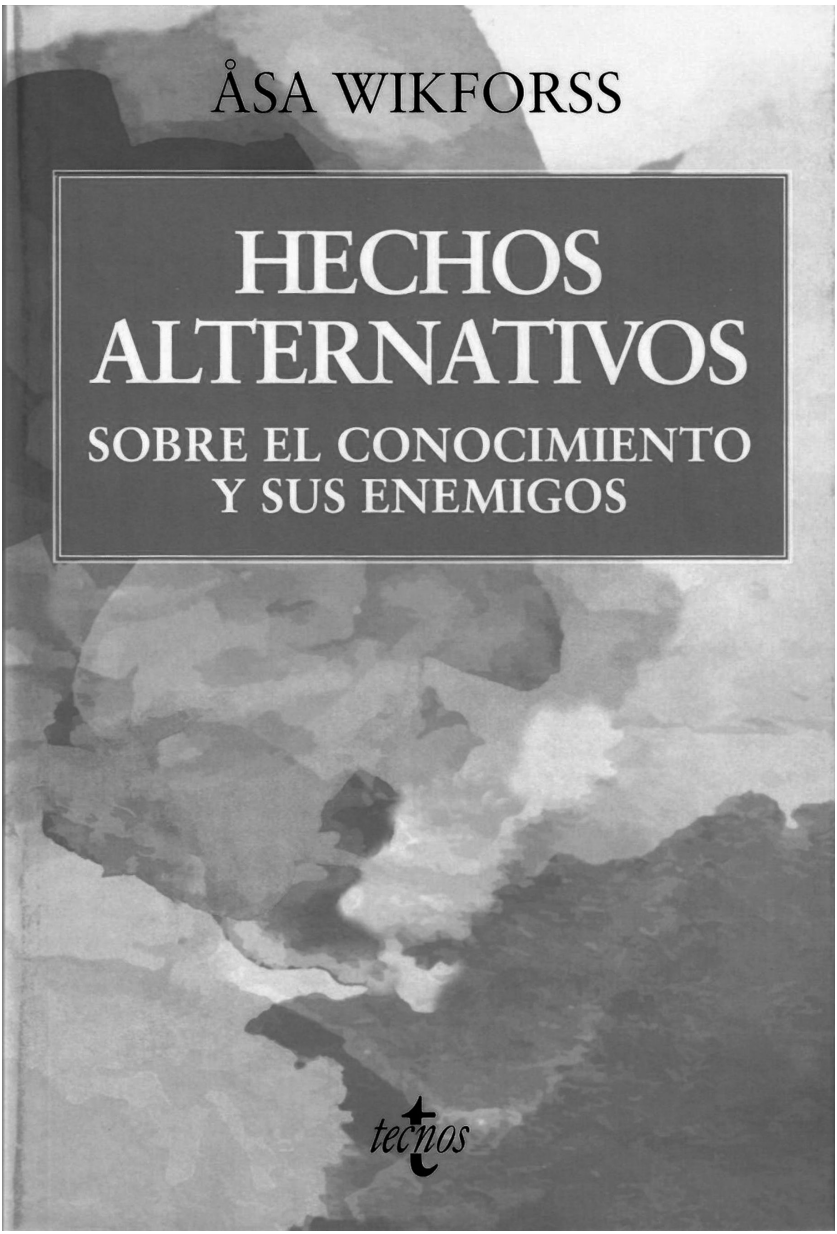
TVERSKY, A. and KAHNEMAN, D. (1974), "Judgment under Uncertainty: Heuristics and Biases"; *Science*, 185, 4157, pp. 1124–31.

UNDORF, M., ZIMDAHL, M. F., and BERNSTEIN, D. M. (2017), "Perceptual Fluency Contributes to Effects of Stimulus Size on Judgements of Learning"; *Journal of Memory and Language*, 92, pp. 293–304.

YEUNG, N. and SUMMERFIELD, C. (2012), "Metacognition in Human Decision-Making: Confidence and Error Monitoring"; *Philosophical Transactions of the Royal Society: B*, 367, pp. 1310–21.

WEGENER, A. (1977), *The Origin of Continents and Oceans*; translated from the 4th revised German edition by J. Biram. New York: Dover Publications, inc.

WILLIAMSON, T. (2016); "Abductive Philosophy", *Philosophical Forum*, 47, 3–4, pp. 263–80.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