Neuroscience and Biobehavioral Reviews 153 (2023) 105363

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Insight and the selection of ideas

Ruben E. Laukkonen[a,*], Margaret Webb[b], Carola Salvi[c], Jason M. Tangen[d], Heleen A. Slagter[e], Jonathan W. Schooler[f]

[a] *Southern Cross University, Gold Coast, Australia*
[b] *University of Melbourne, Melbourne, Australia*
[c] *University of Texas, Austin, United States*
[d] *The University of Queensland, Brisbane, Australia*
[e] *Vrije Universiteit, Amsterdam, Netherlands*
[f] *The University of California, Santa Barbara, United States*

ARTICLE INFO

Keywords:
Insight - prediction - active inference - ideas - heuristics - Aha - problem solving

ABSTRACT

Perhaps it is no accident that insight moments accompany some of humanity's most important discoveries in science, medicine, and art. Here we propose that feelings of insight play a central role in (heuristically) selecting an idea from the stream of consciousness by capturing attention and eliciting a sense of intuitive confidence permitting fast action under uncertainty. The mechanisms underlying this *Eureka heuristic* are explained within an active inference framework. First, implicit restructuring via Bayesian reduction leads to a higher-order prediction error (i.e., the content of insight). Second, dopaminergic precision-weighting of the prediction error accounts for the intuitive confidence, pleasure, and attentional capture (i.e., the feeling of insight). This *insight as precision* account is consistent with the phenomenology, accuracy, and neural unfolding of insight, as well as its effects on belief and decision-making. We conclude by reflecting on dangers of the Eureka Heuristic, including the arising and entrenchment of false beliefs and the vulnerability of insights under psychoactive substances and misinformation.

We do not just think about ideas, we feel them too. Whenever we listen to a presentation by a scientist (or a politician), we quickly sense whether we agree with the ideas being shared. The same is true for our own ideas. When an idea appears in our own minds, we also feel whether that idea is likely to be true, valuable, or exciting, and then decide whether to ignore it, share it with our colleagues, or abandon it. When a new idea comes to mind as *insight* it feels true and immediately imbues us with the sense that the idea is a good one. In this paper we aim to ascribe an adaptive function to such feelings of insight. Specifically, we propose that feelings of insight act as a metacognitive heuristic, leading us toward quickly deciding whether we should trust an idea based on prior learning and context. We term this the *Eureka Heuristic*. We also propose that this heuristic functioning of insight can be explained within a hierarchical active inference model of brain function, thus providing both a cognitive and neurocomputational theory of insight.

The prospect that insight has an adaptive function in idea or perspective selection is partly inspired by recent findings that feelings of insight tend to occur alongside correct solutions (Danek and Wiley, 2017; Laukkonen et al., 2021; Salvi et al., 2016; Threadgold et al., 2018; Webb et al., 2016; Zedelius and Schooler, 2015). These findings, among many others to be discussed, are indicative that feelings of insight may carry important information for the selection of useful ideas. We have indeed tested a number of empirical predictions arising directly out of the Eureka Heuristic perspective, including insight misattribution (i.e., making facts seem true by artificially eliciting insights at the same time, Laukkonen, 2020; 2021; and developing a paradigm for eliciting false insights, Grimmer et al., 2022a,b). We have also found that the embodied intensity of insight predicts accuracy over and above its mere presence, suggesting that the 'volume' of the feeling is somehow scaling with epistemological validity (Laukkonen et al., 2021).

The paper is structured as follows: We begin by discussing the feeling of insight and then describe why it is likely to play an adaptive role in decision-making under uncertainty. We then review the Eureka Heuristic in light of key empirical studies. Drawing on active inference and predictive processing accounts of mind and brain, we outline the possible mechanisms underlying the unfolding of an insight and supporting evidence. We then contextualize our framework with regard to other theories of insight. Finally, we integrate our explanations at the

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* Correspondence to: Gold Coast Airport, Terminal Dr, Bilinga, QLD 4225, Australia.
E-mail address: ruben.laukkonen@scu.edu.au (R.E. Laukkonen).

https://doi.org/10.1016/j.neubiorev.2023.105363
Received 2 March 2023; Received in revised form 19 June 2023; Accepted 15 August 2023

cognitive and neurocomputational levels and discuss how the framework speaks to the development of false beliefs, delusions, and how different contexts might occasion a 'breakdown' in the heuristic.

1. The feeling and function of insight: cognitive level

The scientific literature on problem solving was dominated by a long debate on whether insight represents a distinct type of problem solving, or just an epiphenomenon based on the same cognitive mechanisms as analytical step-by-step solutions (Bowden et al., 2005; Fleck and Weisberg, 2013; Gilhooly and Murphy, 2005; Hedne et al., 2016; Weisberg and Alba, 1981). For example, some have suggested that the distinction between insight and analysis is an oversimplification, and that problem solving methods are manifold (Fleck and Weisberg, 2013). Yet others have argued that the distinction or 'mystery' behind insight is overblown (Weisberg et al., 2013). However, in the last two decades, thanks to advances in methodology, scientists were able to demonstrate that this dichotomy is based on different neural (Bowden and Jungbeeman, 2007; for a review see Kounios and Beeman, 2009), physiological (Salvi et al., 2020; Shen et al., 2018), and behavioral correlates (e.g., Salvi et al., 2015, 2020). Insight also 'feels' subjectively different from step-by-step analytical problem solving. Recent work has thus begun focusing on the reportable subjective qualities that accompany a sudden insight, which may include feelings of certainty and obviousness, relief, surprise, pleasure, and the drive to act (Danek et al., 2014; Danek and Wiley, 2017; Jarman, 2014; Kounios and Beeman, 2009; Liljedahl, 2005; Webb et al., 2016, 2018; Stuyck et al., 2021).

So far only a handful of studies have been explicit about assigning an adaptive function to feelings of insight. One promising approach has been to incorporate the feeling of insight within feelings-as-information theory (Valueva et al., 2016). According to feelings-as-information theory, phenomenology carries information that helps us to efficiently navigate the world and to reason appropriately (Schwarz, 2012). Hunger, for instance, carries information about the organism's nutritional requirements, and feelings of pain and fear help us avoid events that might cause us harm. More subtle feelings like fluency and familiarity also have important functions for decision-making (Hertwig et al., 2008; Reber and Schwarz, 1999). In a similar vein, the Aha! experience was suggested to provide an initial cue that one has solved a problem in order to prepare for sequential verification (Valueva et al., 2016, pg. 207): "… the feeling of insight manifests itself as a signal for high-level processes that the solution is probably found at [a] lower level. This feeling, therefore, may evoke a useful adaptive process."

The insight experience has also been characterized as an emotional reaction regarding the relevance of a solution to the organism's goals (Thagard and Stewart, 2011). This account frames insight as the result of combining novel neural representations, which result in further novel *emotional* neural representations that evaluate the idea in terms of its payoffs. One similarity here is that the insight experience is assigned a higher-order function. However, if the solution is only evaluated in terms of payoffs, then the same emotional reactions ought to be found for analytically derived solutions (i.e., non-Aha! ideas) that are also fulfilling the organisms goals, but this is not so (Webb et al., 2016). Skaar and Reber (2021) also suggested that Aha! experiences may guide problem solvers in the process of discovery by acting as a kind of heuristic cue of type 1 processes. These studies thus provide important building blocks for the Eureka Heuristic because they highlight that the Aha! experience may play a higher-order evaluative function that quickly follows the emergence of a creative idea.

Other relevant work has discussed the possible analogy between insight and intuition (Zander et al., 2016). Both intuition and insight seem to be effortless or automatic rather than relying on analytic or deliberate conscious processing, so it may be that insight is just another form of intuition that permits quick intuitive decisions. However, intuition tends to be more gradual and non-specific, whereas insights are sudden and tend to involve specific reportable content (Zander et al., 2016; Zhang et al., 2016). Unlike intuitions which are often associated with so-called 'system 1′ errors (Kahneman, 2011), insights tend to predict accurate solutions (Danek and Salvi, 2018). Yet, like intuition, seminal work suggested that there must be a certain element of intuition drawn from past experience in any new insightful idea or hypothesis: "Any novel insight must in some sense draw upon what the person already knows, and what is known must be mnemonically encoded." (Bowers et al., 1990, pg. 94). Memory, semantic associations, or spreading activation, have all been implicated in the underlying mechanisms of sudden and accurate insights (Weisberg and Alba, 1981; Yaniv and Meyer, 1987).

One common theme so far is that insights must somehow draw on past experiences or memory in order to provide valuable information for ongoing problem-solving processes. We suggest that the feeling of insight may signal the extent to which our past knowledge and present context *coheres* with the new idea, a kind of higher-order (meta-cognitive) representation about the quality of the idea. The information contained in the insight can then be used adaptively to select from myriad possible ideas, on average resulting in an accuracy advantage. Insights thereby act as the 'line in the sand' that permits adaptive action by issuing a feeling that tracks how well we intuitively agree with the idea in any given context (Valueva et al., 2016). To illustrate, in the case of classical insight problem solving, when one undergoes a restructuring of a problem representation (Ohlsson, 1984), then suddenly one's knowledge coheres with the solution (Aha!), while it did not just a moment before. Thus, it is one's past learning, representations, and assumptions, that determines an insight: The correct representations are needed to determine that an idea is a good 'fit' to the problem (Bowers et al., 1990). This view of insight as a higher-order representation of coherence or fit also tracks well with other meta-cognitive models of feelings of knowing (Koriat, 1993; Metcalfe et al., 1993), fluency (Schwartz and Jemstedt, 2021), and tip-of-the-tongue experiences (Metcalfe et al., 1993; Schwartz and Pournaghdali, 2020). It is also consistent with the adaptive function of feelings more generally (Damasio, 1996; Schwarz, 2012; Slovic et al., 2007). But insight is unique from other feelings in that it represents the subjective quality (defined in detail later) of our own ideas.

This adaptive functioning of insight is perhaps best understood in the context of heuristics and biases (Gigerenzer and Gaissmaier, 2011; Slovic et al., 2007; Tversky and Kahneman, 1974; Whittlesea and Williams, 2001). Insights have in common with heuristics the fact that they are automatic, largely involuntary, linked to emotions, and (we suggest) are foremost adaptive (Schooler et al., 1993; Schooler and Melcher, 1995). Moreover, new evidence is showing that they can also influence memory judgments (in some cases exacerbating false memories, Dougal and Schooler, 2007), judgments about what is true or false (Laukkonen et al., 2020), and even shift worldviews (Laukkonen et al., 2021, 2022), discussed further below. The heuristic view is helpful as it places the insight experience in a larger, temporally extended context and raises many new directions for research.

2. Key empirical evidence

Here we outline a number of key empirical studies that align with the Eureka Heuristic framework, as well as a number of experiments that were designed to explicitly test the ideas.[1] We review evidence of implicit processing, the accuracy of insights, memory effects, misattribution of insights, false insights, and attentional capture. We then outline possible mechanisms underlying the heuristic with supporting neural findings.

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[1] Note that we do not present a systematic review in this paper. Our purpose here is to present a novel theoretical framework that focuses on the feeling of insight, which has only recently come to the forefront of insight research.

2.1. Implicit processing

It is now well accepted that there are processes occurring below awareness that underlie the insight experience and that these processes often cannot be reported (Ball et al., 2015; Schooler et al., 1993). For example, insight moments appear unexpectedly and sometimes while engaged in another task indicating that implicit processes must have contributed to the solution's surprising emergence (Hedne et al., 2016; Laukkonen et al., 2021; Laukkonen and Tangen, 2017; Metcalfe and Wiebe, 1987; Ovington et al., 2018). Solving anagrams—a problem commonly used to elicit insight—also happens in an "all-or-none" fashion, as evidenced by speed-accuracy decomposition (Smith and Kounios, 1996). That is, participants are unable to provide much partial information at different stages of problem solving, and instead show evidence of holistic sudden emergence.

Research on subliminal priming is also revealing. Maier (1931) famously observed that a hint surreptitiously given to people can help them solve the two-string (pendulum) problem. Similar 'priming' effects have been observed in multiple studies since. For instance, experience with one problem can facilitate performance on another problem without subjects being aware of the connection (Schunn and Dunbar, 1996), and subliminally priming a solution to an anagram can induce more insights, again without participants knowing that they were being primed (Bowden, 1997, see also Grant and Spivey, 2003; Hattori et al., 2013). Finally, while monetary rewards are well known to hinder creativity and insight problem solving, when the money is presented subliminally it can increase insights (Amabile et al., 1986; Cristofori et al., 2018).

The implicit processing afforded by periods of incubation (e.g., putting the problem aside and working on another task) can also facilitate insight. Indeed, diary studies of creative individuals indicate that creative ideas routinely occur when individuals are otherwise occupied (i.e. mind wandering), and these ideas are particularly likely to be associated with feeling of insight (Gable et al., 2019). Moreover, a review of 117 studies revealed that an incubation period enhances insight problem solving best if one is occupied by an undemanding task compared to when the incubation is occupied by a demanding task (Bowden, 1997). Studies on the neural correlates of insight also suggest that Aha! moments may be preceded by periods of 'mini-incubation'. For instance, Aha! moments are preceded by alpha activity over the visual cortex and in another study this activity was paired with a higher eye blink rate (Salvi et al., 2015) data that has been interpreted also as periods of incubation (Gilhooly et al., 2019). Even problems with very short problem solving times (e.g., CRA), may be preceded by moving attention away from the target task (looking at nothing behaviors; Salvi and Bowden, 2016) permitting a short period of incubation conducive to insight (Gilhooly et al., 2019).

Implicit processing is important because it highlights why an insight heuristic may be necessary. If an idea appears spontaneously following unconscious 'work', then there ought to be a way for the organism to judge whether the idea can be trusted. Unlike step-wise analytic problem solving where one can decide on a solution based on strategic reflection, the surprising nature of the Aha! experience entails that it needs to be 'intuited' as a good idea in order to distinguish it from other myriad ideas, even competing ideas that may seem analytically a good candidate, but do not 'feel' right.

2.2. Accuracy of insights

One result requiring explanation is the fact that insights are characterized by higher accuracy. For example, 92% of the time people have an insight they are likely to be correct (data retrieved from Salvi et al., 2016 dataset). In their study, Salvi et al. (2016) presented participants with a range of different problems across four experiments, including compound remote associates (CRA), rebus puzzles, anagrams, and visually degraded images. Across all four experiments and each of the problem types, solutions associated with insight experiences tended to be correct more often than those not accompanied by insight. This basic finding is well replicated across many labs (Danek and Wiley, 2017; Laukkonen et al., 2021; Salvi et al., 2016; Threadgold et al., 2018; Webb et al., 2016; Zedelius and Schooler, 2015).

We also recently tested the accuracy of insights using a more embodied approach (Laukkonen et al., 2021). When participants solved problems and indicated their Aha! moments in *real-time* using a dynamometer—a highly sensitive measure of grip strength—the feelings strongly mapped onto the accuracy of solutions (Laukkonen et al., 2021). Intriguingly, the participants also unintentionally gripped the dynamometer more tightly during more intense insights and this incidental embodiment also further predicted the accuracy of their ideas. Therefore, the feeling of insight and its intensity appears to have informational value about the accuracy of new ideas, which makes sense if coherence with past learning is partly driving the intensity of the insight experience.

2.3. Misattribution of insights

If feelings of insight are being used heuristically to select ideas, then it ought to be possible to bias the selection of ideas by artificially eliciting insights. Dougal and Schooler (2007) presented participants with 60 words to memorize, and then provided a set of anagrams to solve followed by a recognition judgment regarding the solution of the anagram. Anagrams that were solved were more likely to be recognized (remembered) compared to the anagrams that were not, suggesting that something about solving the anagram was leading to an 'illusion of prior experience' (replicated in five additional experiments). The mechanism proposed was *discovery misattribution*: The Aha! experience of solving an anagram leads to a false inference of remembering, where participants incorrectly interpret their Aha! feeling as a signal that a word is familiar. Moreover, surprise—a dimension of the insight experience (Danek et al., 2014; Webb et al., 2018)—can also confound memory judgments (Whittlesea et al., 1990, 2005).

As an explicit prediction arising out of the Eureka Heuristic model, we recently showed that artificially induced Aha! experiences could make facts appear truer, even if they were false (Laukkonen et al., 2020). We used anagrams to induce Aha! moments at the same moment that a proposition (e.g., *lithium is the lightest of all metals*) was revealed. The anagram was embedded in the statement in such a way that solving the anagram simultaneously revealed the proposition (e.g., *ithlium* is the lightest of all metals). Participants rated propositions as truer when they solved the anagram themselves, compared to when it was simply revealed (after the participants timed out). The effect was strongest when solving the anagram also elicited an Aha! moment. Thus, participants appeared to misattribute their Aha! experiences to the temporally coincident but irrelevant fact, suggesting that the feeling of Aha! influences one's sense of what is considered 'true'. We then extended this paradigm to axiomatic worldviews, such as "*it is useless to pursue justice*" or "*free will is a powerful illusion*". In three experiments and over 4000 participants, we found that irrelevant Aha! moments lead to a 'ring of truth' that results in greater belief in the presented worldviews (Laukkonen et al., 2022).

2.4. False insights

We have also taken the Eureka Heuristic view to the test by developing a paradigm for eliciting false insights (Grimmer et al., 2022a). In this recent study, participants were first exposed to a list of semantically associated words and then presented with an anagram that *looked* related to the previous list, but was actually unrelated (i.e., semantic priming, White, 1988). This manipulation lead to participants having far more false insights when the priming was present versus absent (Grimmer et al., 2022a). The finding was also replicated in a second experiment, and several replications and extensions have since been conducted (Grimmer et al., 2022b, 2023). Thus, the accuracy of the feeling of insight can be confounded by exposing the participants to misleading information, effectively breaking the heuristic (i.e., the extent to which past knowledge or context was accurately informing the phenomenology).

2.5. Memory and Attention

If the feeling of insight is selecting an idea at the exclusion of others, then insights ought to capture attention and be encoded into memory better than ideas not 'selected'. Indeed, a series of recent studies have found a memory advantage for solutions accompanied by insight (Danek et al., 2013; Engelhard et al., 2019; Kizilirmak et al., 2016). Crucially, the feeling component of insight appears to specifically drive the memory advantage (Danek and Wiley, 2020). There is also growing evidence that feelings of insight can lead to attentional capture and interrupt ongoing trains of thought (Kounios et al., 2006, 2008; Salvi, Beeman et al., 2020; Salvi et al., 2015). For example, insights are paired with specific eye behavior (i.e., eye blink rate, fixations away from the problem area and pupil dilation) indexing external disengagement and a sudden switch toward internal processing mediated by locus coeruleus-norepinephrine (LC-NE) activity (Salvi et al., 2015; Salvi et al., 2020). The LC-NE system is involved during a shift of attention in response to novel and alerting stimuli, such as a loud noise (Aston-Jones and Cohen, 2005; Bouret and Sara, 2005; Devauges and Sara, 1990; McGaughy et al., 2008; Yu and Dayan, 2005). Thus, considering the similarities between quickly switching attention to sudden inputs and the involvement of the LC-NE system, it is likely that the Aha! feeling aids the selection of ideas in awareness specifically by its ability to capture attention.

Taken together, in this section we have seen that the Eureka Heuristic view is consistent with a wide range of evidence, including implicit processing and emergence of insight, the accuracy of insights, misattribution of insights, false insights, and memory and attention effects. Next, we delve into neuro-computational mechanisms of insight and evidence at the neural level.

3. The feeling and function of insight: neural and computational level

In light of the general framework described above, how does the Eureka Heuristic work? Simultaneous to the growing interest regarding insight, there has been a paradigm shift in the cognitive neurosciences, expanding quickly in all directions. This framework integrates processes of the mind, brain, body, and behaviour, under a single process known as prediction-error minimization (Friston, 2010; Hohwy, 2013). As yet, the process of sudden discovery and 'Aha!' experiences that characterize insight (Bowden et al., 2005; Danek et al., 2020; Laukkonen et al., 2021) have not been fully integrated under this Bayesian inferential view of mind (Clark, 2013; Friston et al., 2017; Hohwy, 2013). Here, we sketch the fundamentals of this framework because it shows promise as a context for understanding the dynamics and functions of the Aha! experience including the Eureka Heuristic.

The roots of predictive processing are usually attributed to Helmholtz' (1860) ideas on 'unconscious inference' in perception, but have since been elaborated and tested computationally (Rao and Ballard, 1999), mathematically and hierarchically refined (Friston, 2010), extended to include action (Clark, 2013), emotion (Seth, 2013), and higher cognition (Corcoran et al., 2020; Hohwy, 2013). Applications of predictive processing theory are emerging for psychiatric disorders from anorexia (Gadsby and Hohwy, 2019) to autism (Lawson et al., 2014), as explanations for curiosity (Schwartenbeck et al., 2019) and meditation (Laukkonen et al., 2023; Laukkonen and Slagter, 2021), and applying so-called active inference models are showing success in machine learning and artificial intelligence (Ueltzhöffer, 2018).

Predictive processing theory can be derived elegantly from basic axioms. First, the brain (computationally speaking) does not have any direct way to know what is happening outside itself. That is, it has no way of accessing the world beyond the impressions that bump up against the sensory organs of the body that give rise to ascending signals to the brain. To resolve this problem and to infer the hidden causes of sensation, the brain is proposed to make inferences about what *might* be out there (so-called "hidden states"), and then to test these guesses (predictions) against the sensory input caused by the hidden states. When an error is made, the error signal can be used to revise one's beliefs or expectations about hidden states (i.e., what generated the sensation) and subsequent predictions. The recurrent exchange of ascending prediction errors and descending predictions resolves prediction errors in a way that can be read as Bayesian belief updating (noting that the Bayesian beliefs in question are not propositional, just posterior probabilities[2] that are encoded by neuronal activity). Crucially, this inferential process is extended deep into the hierarchical structure of the brain, such that prediction-error minimization continues on multiple timescales and levels of processing (Badcock et al., 2019; Friston, 2008). Lower levels of the brain's hierarchy encode concrete (e.g., sensory) information, and higher levels encode more abstract and conceptual information (e.g., thinking) (Badcock et al., 2019). Mathematically, long-term prediction error-minimization corresponds to reducing uncertainty and entropy, which therefore ensures the organism maintains a sufficiently "accurate" model for enduring existence (Friston, 2010).

The organism can improve the accuracy of its predictions and thereby reduce prediction error and uncertainty in several ways. One way is to revise its models so that predictions align with the input, known as perceptual inference. Another way is to actively sample the world in such a way that can confirm or refute one's predictions, known as *active inference* (Friston et al., 2016a,b). Here the agent makes predictions about future states of sensory experience and then moves the body (e.g., palpating the world visually with certain eye movements), in order to reduce the error generated by the prediction. The agent thereby creates a kind of self-fulfilling prophecy (think of making the prediction "I'm going to grab a glass of water" and then executing the actions necessary to make the predicted sensory consequences of that action come true). Active inference also extends to thinking, or "mental simulations", wherein one simulates counterfactual events that *could* happen in order to test which courses of action would lead to the best models in the long-term (Corcoran et al., 2020; Metzinger, 2017). This is where the expected prediction errors following an action comes in, where expected surprise is uncertainty. Under active inference, this means that everything we do can be cast as avoiding surprising outcomes and resolving uncertainty. This renders us quintessentially curious creatures because reducing uncertainty over the long-term often involves exposing ourselves to uncertainty in the short term (e.g., learning to speak a new language when moving to a foreign country).

Another way the organism can efficiently manage the stream of prediction-errors is through secondary predictions about how reliable or predictable sensory evidence is, relative to our beliefs (priors). Mathematically, this predictability is known as *precision* and the ensuing '*precision-weighting*' of precise, informative input is equated with attention (Feldman and Friston, 2010) and confidence (Carhart-Harris and Friston, 2019). Physiologically, this precision weighting simply involves affording more synaptic gain to precise prediction errors, so that they have more effect on belief updating. The requisite synaptic gain control is mediated by modulatory neurotransmitters like dopamine (FitzGerald et al., 2015; Friston et al., 2014). In this setting, dopamine can be regarded as scoring the precision afforded beliefs about impending action; so that phasic release of dopamine reflects an increase in the confidence about the consequences of action.

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[2] The posterior probability is the outcome of the Bayesian calculation which is ultimately what is said to be perceived (i.e., becomes part of the generative model).

Recently, Friston et al. (2017) provided an account for the emergence of insight known as "fact free learning." This idea rests on an assumption that the optimization of models (prediction-error minimization) can also occur without new information from outside the body. That is, no new facts are necessary for the system to continue refining its understanding. One can see how this is important for sudden learning events like insight, in which one can discover something seemingly novel while in the shower, or just before falling asleep (Ovington et al., 2018). Fact free learning occurs through Bayesian model reduction—a simple and efficient form of Bayesian model selection (Friston et al., 2016a,b).

Bayesian model reduction entails finding more parsimonious and generalizable explanations of the data already possessed. It is a kind of 'active incubation' where one's knowledge is tested against itself—"only of itself and on itself'' (Poincaré, 1908–1952, p. 22, quoted in Sandved-Smith, 2015)—in order to find simpler explanations. Thus, just as a kind of 'learning' can occur during sleep through memory consolidation and synaptic pruning (Hobson and Friston, 2012; Tononi and Cirelli, 2006), insights may follow a sub-personal (i.e., implicit) process of optimization. This is achieved by selecting between models (i.e., prior hypotheses or explanations) that render existing observations (data) the least surprising through Bayesian model reduction (Friston et al., 2016a,b). This model reduction and ensuing model selection is the mechanism that permits a restructuring to take place, which ultimately results in a new discovery at a higher-order level of sentience (Friston et al., 2017). By modelling and simulating Bayesian model reduction in an abstract rule learning task, an artificial agent showed the hallmarks of sudden learning associated with insight (Friston et al., 2017).

The above account provides a candidate formal explanation of how a sudden discovery can emerge from unconscious processes. Unlike inferring states of affairs 'out there' beyond our sensorium—and unlike learning the parameters of our generative models—the act of Bayesian model selection is a discrete process: selecting discrete, well-defined structures, models or hypotheses. This means that discovering a simpler explanation, for sensations sampled to date, is an event that can only happen at a particular moment. Crucially, however, the Bayesian reduction account does not explain the *feeling* or *function* of insight.

Although Friston et al. (2017) show that an artificial agent demonstrates the hallmarks of Aha!, they define this as a 'qualitative transition' in knowledge and understanding. However, not all solutions that appear suddenly are accompanied by an Aha! experience (Laukkonen and Tangen, 2018; Laukkonen et al., 2021) and the relationship between restructuring and feelings of Aha!, although usually present, is rather modest (Cushen and Wiley, 2012; Danek et al., 2020; Laukkonen et al., 2021). Moreover, 'Aha!' moments can have recursive consequences beyond the emergence of an idea, by affecting belief, memory, and judgment (Danek and Wiley, 2020; Dougal and Schooler, 2007; Laukkonen et al., 2021b; Laukkonen et al., 2020). In short, Bayesian model reduction only addresses the preceding implicit belief updating and selection processes (the transition from incubation to illumination). It does not account for the 'experience' of the Aha! moment and its downstream consequences.

4. Insight as precision

Here, we consider how Aha! experiences could be accounted for within the active inference framework in a way that includes the experience. We take it for granted that any novel model or hypothesis appearing in the mind must be triggered by a qualitative change in belief updating derived from implicit (e.g., Bayesian model reduction) processes unfolding below awareness. We will read this trigger as a prediction error,[3] because prediction errors are the only information that 'ascend' the hierarchy and therefore act as input to revise beliefs at high levels of a hierarchical generative model, "deeper" in the brain. To understand why Bayesian model reduction necessarily entails ascending prediction errors it is helpful to think about what constitutes a good model. A good model maximises the likelihood of data—or minimises surprise. This (marginal) likelihood is accuracy minus the complexity. In Bayesian model reduction, there is no concurrent data to worry about and therefore the imperative for selecting novel models is to reduce complexity and provide a simpler account of the sensorium; in other words, 'join the dots', 'see common themes', etc. This imperative underwrites the ability to generalise to new data and precludes what statisticians call 'overfitting'. However, it also entails the loss of accuracy, in relation to previously observed data. It is this loss of accuracy that engenders a change in prediction errors that can be registered at high levels of hierarchical processing.[4]

In this setting, a novel model plays the role of a change that underlies a classical oddball or sensory prediction error (Garrido et al., 2009; Näätänen and Alho, 1995) in that it is surprising in light of what one predicted just a moment before. Associating Bayesian model reduction with an internal event that is registered or 'recognised' is also consistent with evidence that problem restructuring elicits a component thought to reflect a higher-order prediction error, namely the n320 (Mai et al., 2004; Qiu et al., 2006), and that Aha! experiences are associated with meta-cognitive prediction errors (Dubey et al., 2021). Interestingly, related P300 responses are thought to underlie the brains responses to a change in context that calls for a reorientation of attention (i.e., precision weighting). In the context of the Aha! moment, the *restructuring* in question calls upon the implicit *structure learning* associated with Bayesian model selection (Gershman, 2017; Smith et al., 2020; Tervo et al., 2016).

A prediction error arising from implicit processing at lower-order levels provides a mechanistic explanation for the recognition of restructuring at a conscious higher-order level. However, it does not yet provide an explanation for the distinct phenomenology, function, and scaling intensity of the Aha! experience. The best candidate for the Aha! experience is perhaps the second-order inference (i.e., metacognitive inferences about inferences), known as precision-weighting. Under this view, it is the expected precision of the ascending prediction error—i.e. its expected uncertainty given prior knowledge—that underlies the feeling of insight. In other words, to experience 'insight', one has to have a generative model that recognises belief structures have changed, so that precision can be deployed at the lower hierarchical levels that evince the structure learning. In short, there has to be a hidden state of the world (e.g., "I've just had an insight") that explains the changes in prediction errors from lower levels that result from the subpersonal 'insight' afforded by Bayesian model reduction.

Precision is associated with attention, confidence, and is believed to be encoded by neuromodulators like noradrenaline and dopamine (discussed further below)—and therefore an idea with high precision ought to capture attention, feel right, feel good, and inspire confident action (Parr and Friston, 2017a); either motor action or autonomic (Seth and Friston, 2016). Computational formulations in the context of decision-making indicate that the precision of beliefs about action

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[3] More generally, in belief propagation and variational message passing implementations of belief updating in active inference, the prediction error stands in for free energy gradients, which the brain is trying to descend. This gradient descent minimizes free energy or maximises the marginal likelihood or evidence for brain's generative models. This is sometimes known as self-evidencing (Hohwy, 2016).

[4] We thank Karl Friston for pointing this out to us.

reflects its expected value or utility (Friston et al., 2014), consistent with the secondary component of reward prediction errors (Schultz, 2016). This fits comfortably with the fact that insights seem intrinsically valuable when they arise. An idea with low expected uncertainty (high precision) should also be objectively accurate on average given reliable prior and contextual knowledge, see Fig. 1. In some fields, this kind of (intrinsic) value is known as intrinsic motivation (Oudeyer et al., 2007; Schmidhuber, 2010; Schwartenbeck et al., 2019), of the sort that underwrites exploration and epistemic affordances.

To briefly take the model one step further, consider the question: Who or what is it that recognizes that an insight has occurred? How is that we can reflect on whether the insight phenomenology is reliable, or not (as is occurring in this paper)? Recent work extends hierarchical active inference to include an additional layer of parametric inference that corresponds to meta-awareness (Sandved-Smith et al., 2021). For example, there are objects of perception, then there is attention in relation to that perception, and there is also meta-awareness of changes in attentional deployment (e.g., noticing that "my attention has wandered", cf. Schooler et al., 2011). Likewise, in the case of insight, we have an idea, we also have a feeling about that idea, and we can also have a meta-awareness about the feeling (i.e., how confident am I that this feeling is trustworthy in this context?). This next level of inference that corresponds to meta-awareness is simply another layer of precision-weighting over the feeling (Sandved-Smith et al., 2021). Such high-order representations of mental states are necessary to both recognise a quantitative change in ascending prediction errors and generate descending predictions of precision to instantiate an attentional set—a set that may be necessary to consolidate the insight and imbue it with a sense of veracity. This high-order aspect of hierarchical predictive processing is the same architecture that has been proposed for phenomenal experience. Such high level representations are necessary to recognise various states of mind (e.g., mind-wandering or insight experiences) and upon which mental or covert action can be conditioned (e.g., what one pays attention to, Sandved-Smith et al., 2021). In this sense, the phenomenal experience is both cause and consequence; much in the same way that various affective states of mind recognise and cause interoceptive signals via interoceptive inference (see Fig. 1, Seth, 2013).

5. Attention, dopamine, and neural evidence

An important caveat to our selective review below is that the neuroscience of insight is still in its infancy and there are notable challenges to studying it under controlled conditions (Weisberg, 2013[5]). Moreover, these methodological challenges also lead to considerable heterogeneity between studies, likely because insight is hard to 'pin down' from all the associated processes before, during, and after it occurs, as well as differences between tasks used to elicit insight (Sprugnoli et al., 2017).

A key assumption within the active inference framework is that first-order precision-weighting reflects attention (Feldman and Friston, 2010; Limanowski and Friston, 2018; Parr and Friston, 2017). Consistent with the high expected precision, insights are preceded by turning attention inward possibly preparing attentional resources for the incoming insight (Kounios et al., 2006; Kounios and Beeman, 2014; Salvi et al., 2015). Participants show less eye movements and more blinking 2 s prior to the onset of an insight compared to an analytic solution (Salvi et al., 2015). Insight solutions are also associated with increased alpha activity between 1.4 and 0.4 s over right posterior cortex before the solution appears (Jung-Beeman et al., 2004), which may be indicative of suppression of external inputs or 'sensory gating' (Salvi et al., 2015; Kounios and Beeman, 2014).

Consistent with the hierarchical dynamics of insights as revising the precision of prediction errors, problem restructuring elicits an error related negativity that may reflect a higher-order precision-weighted prediction error. In one study, when participants solved riddles and the eventual solution was inconsistent with their mental set, the solution elicited a larger negative ERP deflection between 250 and 500 ms (Mai et al., 2004). In a similar design with a much larger sample ($n = 130$), solutions that triggered restructuring also invoked a larger N320 ERP (Qiu et al., 2006). These findings indicate (see also, Dietrich and Kanso, 2010) that at least restructuring, a key characteristic of a sudden solution, elicits a neural response consistently found when participants make prediction errors (Holroyd and Coles, 2002). The results make sense if one's metacognitive levels of processing are 'surprised' by the novel solution appearing in mind following implicit processing. There is also evidence that the emergence of insight correlates with activation in temporal and usually right hemispheric regions (Jung-Beeman et al., 2004; Kounios et al., 2008; Kounios and Beeman, 2014; Subramaniam et al., 2009), indicative of coarse semantic integration (Kounios and Beeman, 2014). Activation in such integration hubs—also corroborated by late ERP components such as the N400 (Sprugnoli et al., 2017)—is consistent with the temporal unfolding of insight from lower-level regions to higher-order regions.

As noted above, precision-weighting is believed to be mediated by neuromodulators such as dopamine (FitzGerald et al., 2015; Friston et al., 2014; Friston et al., 2012). That is, the degree of dopaminergic activity associated with a new idea may reflect its uncertainty given prior-belief (Friston et al., 2012), or in other words, its salience. Indeed, a review of the neural correlates of insight points to a consistent association between Aha! moments and activations within the salience network (Sprugnoli et al., 2017). Dopamine is known to play a key role in reinforcement learning as a result of so-called "reward prediction errors" (Schultz, 2016), it is also associated with confidence, accuracy, and pleasure (Lak et al., 2017), and—in the active-inference framework—dopamine plays an important role in model selection and action (FitzGerald et al., 2015; Friston et al., 2014; Friston et al., 2012). The reason that we focus on dopamine is that the experience or recognition of an insight calls for covert or mental action in the form of attentional redeployment of precision. This mental action entails beliefs about action—sometimes referred to as planning as inference (Botvinick and Toussaint, 2012). Dopamine may play a special role in encoding the precision or confidence in beliefs about overt or covert action. This role of dopamine fits well with the phenomenology of insight (pleasure, confidence, and drive to act, Danek and Wiley, 2017; Oh et al., 2020). Moreover, according to our account the surprise dimension of the insight experience is associated with the prediction error, whereas the pleasure and confidence dimensions are associated with precision-weighting. According to this formulation, pleasure and confidence should predict the *accuracy* of insights more than surprise, which is consistent with recent work (Danek et al., 2017; Webb et al., 2018).

There is also preliminary evidence that insight experiences are associated with the reward circuit and therefore the dopaminergic response (Cristofori et al., 2018; Oh et al., 2020). Participants with high reward sensitivity showed an anterior frontal burst of gamma-band activity approximately 400 ms prior to reporting a solution derived through insight. This activity was taken to reflect an insight-related reward signal because it was uniquely present in the high reward sensitivity population and because source reconstruction localized the effect to orbitofrontal cortex, a region associated with "…reward learning and hedonically pleasurable experiences such as food, positive social experiences, addictive drugs, and orgasm" (Oh et al., 2020, pg. 1). Of note is also the fact that insights are predicted by changes in pupil dilation (Suzuki et al., 2018; Salvi et al., 2020), which has recently been

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[5] For example, Weisberg (2013) critiqued early neuroscientific work for an imprecise use of the subtraction method, leaving possible confounding explanations for neural differences.

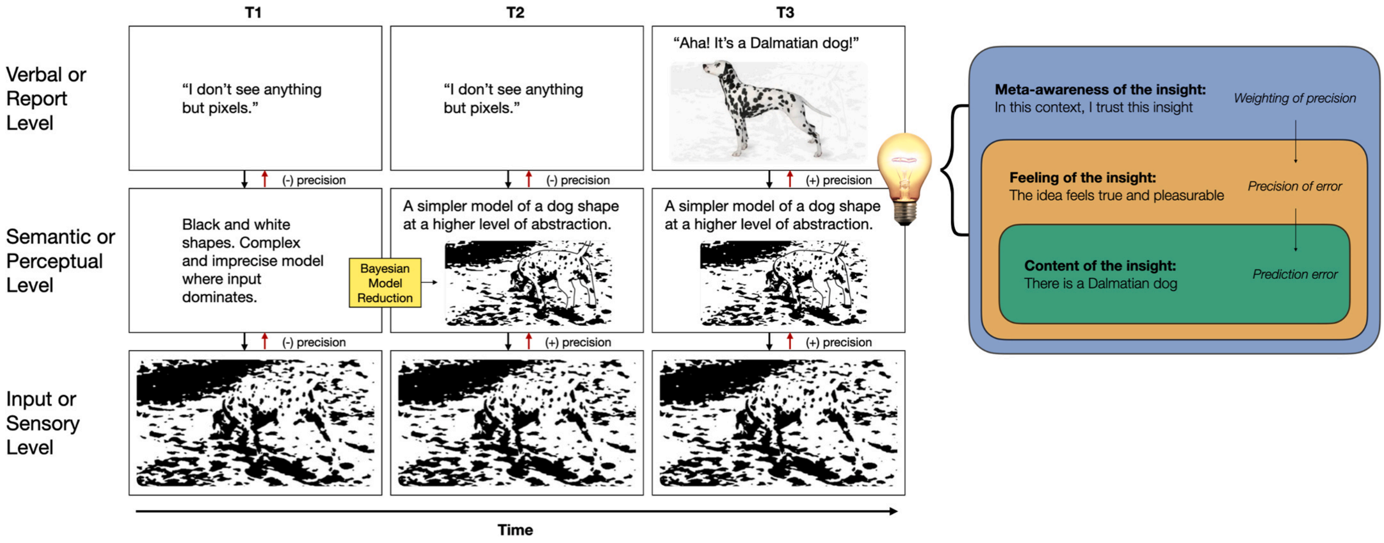

Fig. 1. On the left side, we illustrate a simplified version of three coarse levels of a predictive hierarchy and the changes within those three levels over time, using the classic Dalmatian dog illusion. The Black vertical arrow represents predictions derived from the current model and the red arrow represents prediction errors. The bottom figures highlight the unchanging input of pixels at the early sensory level. At the next "semantic or perceptual level" we see a change from T1 to T2 following Bayesian model reduction. A new simpler, less complex, and more parsimonious model of the black and white "blobs" or pixels emerges at a slightly higher level of abstraction (i.e., the shape of a dog). At the highest verbal or report level we see a shift from T2 to T3 from "I don't see anything but pixels" to a "Dalmatian dog!": The reduced model of the Dalmatian dog leads to a precise prediction error and a corresponding Aha! experience as the higher-order verbal model restructures. On the right side, we present additional nested levels of inference about the precision of an idea, which brings to light the role of meta-awareness in evaluating the reliability of feelings of insight (discussed below). Overall, the figure illustrates the gradual emergence of an insight through changes at different levels of the predictive hierarchy over time, involving Bayesian reduction and ascending precision-weighted prediction errors.

linked to inferences of precision (Vincent et al., 2019).[6] Thus, the rewarding, inspiring, confidence-inducing, and objective veracity of insights may be explained by dopamine modulated expected-precision of a new idea, a new hypothesis, or a new plan. Support for the precision-weighted prediction error model of Aha! is summarised in Table 1 below.

Table 1
Aha moments as dopaminergic precision.

Mechanism	Evidence	Citation
Precision reflects uncertainty given prior learning	Insights are accurate (on average)	Salvi et al. (2016);Danek and Wiley (2017); Laukkonen et al. (2021)
Precision is experienced as felt confidence	Insights feel obvious and increase confidence	Webb et al. (2017); (2018); (2021);Danek and Wiley (2017)
Dopaminergic modulation of precision	Insights feel pleasurable	Skaar and Reber (2020); Gick and Lockhart (1995); Shen et al. (2016)
Precision drives model selection	Insights affect beliefs Insights are remembered	Laukkonen et al. (2020); Danek et al. (2013); (2020)
Precision reflects attention and salience	Insights capture attention and correlate with salience network activation	Kounios et al. (2006);Salvi et al. (2015);Salvi and Bowden (2016)
Precision prepares action	Insights promote drive	Danek and Wiley (2017)
Dopaminergic modulation of precision	Insights are associated with the reward system	Cristofori et al. (2018);Oh et al. (2020)

6. Models of insight

Although there are many models of insight (e.g., Chronicle et al., 2004; Fleck and Weisberg, 2013; Hélie and Sun, 2010; Hélie and Sun, 2010; MacGregor et al., 2001; Ohlsson, 1984), there is a distinction to be drawn here between accounting for insight problem solving and insight phenomenology (see Laukkonen and Tangen, 2018, for an empirical dissociation of the two). While there are several models of insight as a cognitive process, measured as ability to solve insight problems (e.g., Chronicle et al., 2004; Fleck and Weisberg, 2013; Hélie and Sun, 2010; Ohlsson, 1984), there is only one predominant competing perspective on the phenomenology of insight, though ultimately these two views may be complimentary. Topolinski and Reber (2010) outlined a *processing fluency* account of insight. According to this account, cognitive processing is disfluent when the solution to a problem is unclear. When the solution occurs, there is a sudden increase in processing fluency (ease of thinking through a problem space). It is this sudden increase in processing fluency that increases those affective components that are frequent cornerstones in defining insight (i.e., positive affect, judged truth of a solution, and confidence in a response). The processing fluency account is grounded in many experiments around perceptual fluency; particularly findings that indicate manipulating fluency creates a sense of cognitive ease, pleasure, and confidence in the solution (Reber et al., 1998; Reber and Schwarz, 1999; Topolinski and Strack, 2009).

The processing fluency account makes promising predictions about situations that might elicit illusions of insight, for example by artificially increasing the fluency at the moment of solution. One limitation of bundling insight with fluency is that there are still important differences in phenomenology. Insights give rise to drive, inspiration, and can be a source of deep epistemic satisfaction (think of Archimedes racing naked through the street) that seem uncharacteristic of simply ease of processing (Danek and Wiley, 2017; Webb et al., 2018). The fluency account has some further limitations. For instance, it is not clear why only problems that follow implicit processing would lead to an increase in fluency and thus insight experiences. Given a fluency account, both analytic problem-solving and insight problem-solving result in an

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[6] These papers also bring to light a potential role of noradrenaline (and the LC-NA system more broadly) in the alerting and arousing components of an insight experience.

increase in processing fluency once the solution is obtained. The fluency account also does not speak to effects on attention, eye movements, and neural correlates reviewed above.

Fluency also cannot easily explain why an insight can be barely noticeable in some cases, and phenomenally large and important in others (e.g., Eureka moments, mystical experiences, psychotherapeutic insights, and metaphysical insights). For example, Andrew Wiles describes his discovery of the solution to Fermat's last theorem in 1994 as follows, *"At the beginning of September I was sitting here at this desk when suddenly, totally unexpectedly, I had this incredible revelation. It was the most important moment of my working life. Nothing I ever do again will. I'm sorry."* Andrew Wiles fights back tears throughout the video and in the end turns away from the camera because recounting the experience evokes a powerful emotional response. There is an apparent incongruity between the sheer emotional weight of some insight moments and the effects we observe (or would expect) from changes in fluency. Whereas, if we conceive of insight as a sudden reduction in uncertainty marked by an increase in dopaminergic precision-weighting, then the 'rush of insight' makes sense. In our view, insights play a key role in model selection, i.e., transformations of one's belief structures. Therefore, it is understandable that insights can alter worldviews (Laukkonen et al., 2021), transform the mind following practices like meditation or ingestion of psychedelics (Tulver et al., 2023) and alter metaphysical beliefs (Timmermann et al., 2021). If insights can mark fundamental changes to one's understanding of reality, then it would be, we think, remise to reduce insight to an increase in processing fluency.

Another relevant model proposes that insights correspond to metacognitive timing prediction errors (Dubey et al., 2021). The authors provide a valuable building block for our framework by casting insights as positive prediction errors that emerge due to discovering a faster-than-expected solution to a problem. This contradiction to one's metacognitive model leads to a feeling of surprise reminiscent of insight. While our account also brings to light the fact that prediction errors are key to the insight story, there are important differences. In brief, the idea that the feeling of insight is a meta-cognitive prediction error (only) about *time* leaves some key empirical results without an explanation. For example, why would solving a problem surprisingly fast correlate with solution accuracy, as is robustly the case with insight? Moreover, there is no obvious reason why a temporal misprediction should evoke confidence, obviousness, or drive (or any of the powerful phenomenology described above). Aha! moments can also occur unexpectedly about many things long forgotten, such as a realization about one's childhood or a problem one has (meta-cognitively) already given up on. Finally, timing errors do not seem to explain why feelings of insight can affect irrelevant beliefs (Laukkonen et al., 2020, 2022) or mark progress in psychotherapy, meditation, or psychedelic therapy (Tulver et al., 2023; Roseman et al., 2018). In sum, we agree with casting the content of insight as a prediction error, but our account takes the next step by explaining the *feeling* of insight and its function. That is, insight phenomenology is a more general marker of a sudden and surprising *reduction* in prediction errors (uncertainty), quantified as precision.

7. The Insight Fallacy

The mathematician and Nobel laureate John Nash was famously asked why he believed that he was being recruited by aliens to save the world. His response powerfully illustrates the recursive danger of the Eureka heuristic. He said that, *"…the ideas I had about supernatural beings came to me the same way that my mathematical ideas did. So I took them seriously"* (Nasar, 2001). Here, John Nash may have committed what we term the *insight fallacy*. Nash concluded that an idea is true solely because it occurred to him with certain phenomenology, in this case the same phenomenology as his previous mathematical discoveries. Similar fallacious reasoning is also observable with other feelings. For instance, fear is an adaptive signal of a dangerous or challenging situation but is also sometimes unwarranted or irrational, and in severe cases, debilitating (e.g., speaking in public). The same is not so obvious for feelings that accompany our ideas when they arise. The insight moment, like fear, may be a helpful signal that perhaps we have discovered something important. However, if there is overwhelming contradictory evidence, or one is suffering from mental illness (John Nash was diagnosed with schizophrenia in 1959), then it is likely that no matter how intense our revelation, the contents of our idea will remain untrue. Just as a person might experience a profound fear of elevators, the intensity of the fear does not make the elevator dangerous. Likewise, if one is suffering from delusions, or they have been misled with false information, then the explosiveness of the idea—the inferential precision estimates—are no more likely to make it true (Gable et al., 2019; Grimmer et al., 2022a; Webb et al., 2021).

The consequences of false insights can also be dire. Consistent with the insight as precision framework, when an insight moment occurs, subjects are less likely to accept an alternative solution to the problem and are more likely to stick with (Hedne et al., 2016), and remember (Danek and Wiley, 2020), solutions that are similar to their insight. Insights also promote inspiration and provide a drive towards action (Danek and Wiley, 2017), consistent with dopaminergic model selection (Haarsma et al., 2021). Thus, relative to an incorrect-but-analytically derived idea, when a false insight occurs, it may be more difficult to change the person's mind and to prevent them from behaving as if the solution were true. There are many promising avenues of research here, which we discuss below.

8. Discussion

The word Eureka originates in Ancient Greece from the word εὕρηκα (heúrēka), and before that from heuriskein, which means "I find." Heuriskein is also the ancient origin of the word heuristic, which refers to shortcuts that help humans to solve problems. The shared origin of the two words Eureka and heuristic may point to a forgotten wisdom about the nature of the insight experience, namely, that humans use the feeling of Eureka as a heuristic signal to help them select from myriad thoughts and ideas appearing in awareness. We have proposed that feelings of insight signal that one's past experience and knowledge is consistent with a new idea via the mechanism of dopaminergic precision-weighting within the active inference framework, which is consistent with the phenomenology of insights (Webb et al., 2018), attentional capture (Salvi et al., 2015; Salvi, Simoncini et al., 2020; Salvi and Bowden, 2016), confidence (Danek and Wiley, 2017), memory effects (Danek and Wiley, 2020), the accuracy of insights (Laukkonen et al., 2021; Salvi et al., 2016), the neural unfolding of insight (Dietrich and Kanso, 2010; Mai et al., 2004; Qiu et al., 2006), and their effects on decision-making (Laukkonen et al., 2020, 2022).

Human experience is filled with rich phenomenology, bodily sensations, and emotions, which guide our decisions and help us to intuitively navigate complexity and uncertainty. The ability to feel is important in many (if not all) domains of judgment and decision making (Kahneman, 2011; Slovic et al., 2007; Damasio, 1996). In the heat of the moment, the Aha! experience may be all that we have to navigate the selection of our ideas. And since insights usually follow implicit processing and appear unexpectedly, we ought have a way to evaluate whether the idea can be trusted (Smith and Kounios, 1996). Insight phenomenology is very well placed to play this role as a metacognitive heuristic for evaluating new ideas given prior learning, permitting adaptive action.

To explain the mechanics of the heuristic, we have extended the computational framework of Bayesian model reduction (Friston et al., 2017) to include the *feeling* of insight as dopaminergic precision; namely, *felt uncertainty* (Solms, 2019). That is, insight may be derived through implicit Bayesian model optimization "…much like a sculpture is revealed by the artful removal of stone" (Friston et al., 2017, pg. 2669). Solutions (prediction errors) derived through model optimization are then evaluated based on prior learning at a higher-order level, quantified as expected precision. This provides a functional role for the feeling of insight as an estimate about the confidence in our beliefs about the lived world afforded by a new idea given past learning. From a decision-making perspective, Aha! moments therefore directly reflect reductions in expected epistemic uncertainty, making for a good heuristic (Laukkonen et al., 2021).

9. Predictions and future directions

How can the described framework be tested? A straightforward prediction given the dopaminergic precision-weighting hypothesis is that substances that tonically increase activity in dopamine receptors ought to increase the precision-weighting of new ideas, at a possible cost to fidelity (e.g., cocaine, or even caffeine, may make our ideas feel truer on average). Yet other drugs, such as cannabis and psychedelics may increase the expected precision—the feeling of insight—of new ideas by relaxing existing priors (Carhart-Harris and Friston, 2019). Indeed, both cannabis (Heng et al., 2023) and psilocybin (Mason et al., 2021) increase the perceived quality or novelty of one's own ideas without improving quality. Moreover, psilocybin increases feelings of spontaneous insights, which may indicate a risk of increased false insights (Mason et al., 2021). Another novel hypothesis is that an agent who naturally forages for information that improves its models ought to be guided by their phenomenology of insight because precision-weighting indicates uncertainty reduction and hence drives model selection and action (Fitz-Gerald et al., 2015; Friston et al., 2014; Friston et al., 2012). An experiment could provide participants with different courses of action (e.g., to move left or right). If one of the options (e.g., left) leads to more Aha! experiences on average (e.g., by embedding visual stimuli that elicit Aha! moments), and the stimuli are otherwise matched, participants ought to forage for insights by moving left more than right. Such a hypothesis is both empirically and computationally tractable and would demonstrate that the insights guide action for epistemic goals. Moreover, the strength of the bias associated with insight could be exacerbated via substances that increase dopamine firing, effectively 'overweighting' the informational content of insights.

Another assumption of our framework is that the arising idea and the Aha! experience, although related, are dissociable properties of insight (Danek and Wiley, 2020; Gick and Lockhart, 1995; Laukkonen et al., 2021a; Laukkonen and Tangen, 2018). Specifically, the novel information in the insight is reflected in the prediction error (Mai et al., 2004), whereas the feeling reflects expected precision of the prediction error, given prior knowledge. One possibility is that subcortical structures of the dopaminergic pathway reflect the strength of the feeling of Aha! (e.g., nucleus accumbens, Tik et al., 2018), whereas the 'content' and contextualisation of the insight is correlated with integration hubs such as the temporal cortex (Kounios and Beeman, 2014) and later ERP components (Sprugnoli et al., 2017). After insight occurs, we may also see further integration at yet higher-order levels marking a new conscious belief. During this post-insight phase (e.g., in the 2 s following insight) we may expect activity in regions of the default mode network, such as medial prefrontal cortex (Dietrich and Kanso, 2010; Mai et al., 2004). Here the idea may be integrated with one's self-model and trigger top-down decisions given the new insight.

An important direction for future work, behavioural, cognitive, phenomenological, and neural, is the post-insight phase of decision-making. This endeavour to research the impact of insight, although novel to the field of problem-solving and creativity, is central to the construct of insight in other fields such as psychotherapy, meditation, and mystical experiences (Laukkonen and Slagter, 2021; Tulver et al., 2023). In psychotherapy for example, the consequence of insight to the patients recovery is taken to be of central importance and is a moderate predictor of success in treatment (Jennissen et al., 2018). Moreover, insights on psychedelics are related to their success in reducing alcohol consumption (Garcia-Romeu et al., 2019), smoking (Noorani et al., 2018), and overall therapeutic success (Roseman et al., 2018). However, most traditional insight research still relies on toy problems such as compound remote associates and riddles. In order to investigate the impact of insight may therefore require the development of new materials where the insights induced are more meaningful to the individual (Tulver et al., 2023).

In the spirit of heuristics and biases, another promising direction entails identifying the key variables that predict the accuracy and inaccuracy of insight moments. Two fruitful avenues in this regard are investigating the circumstances leading to accurate Aha! moments and discerning concomitants that distinguish true from false insights. As discussed, Eureka moments are more likely to be accurate if they occur on the heels of accurate information (Grimmer et al., 2023; Grimmer et al., 2022a,b). Disconcertingly, the abundance of fake news may therefore be seeding misleading Aha!s by constructing a knowledgebase that coheres with—increases expected precision of—incorrect ideas. As Lazer et al., (2018, p. 1094) note: "The rise of fake news highlights the erosion of long-standing institutional bulwarks against misinformation in the internet age." Thus, in the wrong context, the Eureka heuristic may reinforce the integration of misinformation, potentially motivating people to more deeply 'dig their heels in' to fictitious views via mis-informed precision estimates (Hedne et al., 2016). As telling fact from fiction is becoming increasingly challenging, future research might profitably examine the ease with which false factoids can be strung together to encourage false Eureka experiences, and the impact these insights can have on entrenching misinformation.

With respect to the concomitants of Eureka experiences, it seems likely that altered states of mind may also increase the likelihood of false Aha!s. As William James observed, under the influence of nitrous oxide one can have seemingly profound insights only to be left with nonsense when the gas wears off:

> "…the keynote of the experience is the tremendously exciting sense of an intense metaphysical illumination. Truth lies open to the view in depth beneath depth of almost blinding evidence. The mind sees all the logical relations of being with an apparent subtlety and instantaneity to which its normal consciousness offers no parallel; only as sobriety returns, the feeling of insight fades, and one is left staring vacantly at a few disjointed words and phrases." (James, 1979, p. 294)

Seemingly demonstrating the truth behind his musings above, the otherwise perspicacious James attempted to capture his deep insights during nitrous oxide, recording what later appeared to most sober minds (including his own) as largely gibberish (see James, 1979, p. 296). Of course, it is possible that James was having a genuine Eureka experience that his written words were (uncharacteristically) unable to capture. However, from the vantage of the Eureka heuristic it seems possible that many epiphanies that arise from nitrous oxide and other altered states occur because the intoxicant induces an epiphany-like state which then leads to a false inference of veridicality. Given the precision-weighting mechanism, which is itself thought to be modulated by dopamine, it makes sense that insight processes may be meaningfully altered by psychoactive drugs. Indeed, Haarsma et al. (2021) recently found direct evidence of impairments in learning, modeled as impairments in precision-weighting, following a dopamine antagonist. Learning from precision-weighting also appeared to be impaired in participants who suffer from psychosis. Related to James' reflections of his own seemingly transient insights is the fact that we can reflect on the veracity of our insights. This 'meta-awareness' component gives rise to many new research questions involving the capacity to monitor one's own insights and their epistemic value (Sandved-Smith et al., 2021).

Future research might therefore profitably examine Aha! experiences associated with states induced by psychedelics, cannabis, or other mind-altering substances. In some cases, the capacity of altered states to elicit a sense of significant discovery may also foster bold thinking which may, at least occasionally, lead to important genuine insights (Carhart-Harris and Friston, 2019). For instance, there are many examples of patients suffering from depression reporting profound and transformative insights regarding their condition under the influence of psilocybin or ‘magic mushrooms’ (Watts et al., 2017). Besides externally induced states of ‘insightfulness’, certain meditative practices are also associated with experiences of insight (Laukkonen and Slagter, 2021), the veracity or advantageousness of which is an important question given the now prevalent practice of mindfulness (Van Dam et al., 2018).

In sum, we have provided a perspective on insight that gives it a unique function in selecting ideas from the stream of consciousness given past knowledge, via the mechanism of dopaminergic precision of prediction errors. This framework explains how humans may be using their feelings of insight to heuristically select ideas for quick and efficient action. The heuristic view of insight also highlights many ways in which it can lead to false beliefs. However, we acknowledge that a poet, or an artist, might be sincerely opposed to any suggestion that they should justify their idea or have it verified for accuracy. Moreover, some states of sudden knowing may be deeply plagued by their incommunicability or ineffability. The distinction between true and false insights hence becomes increasingly blurry outside of the domain of problem solving. Nevertheless, it is possible to imagine that there is also a positive correspondence (on average) between our inner sensations of insight and the value society attributes to new ideas or creative works, should that be of interest to the artist or inventor.

Acknowledgments

JS is supported by the Templeton Religion Trust (#TRT0487). We thank an anonymous reviewer for encouraging us to relate our ideas to the notion of phenomenological experience and meta-awareness within active inference.

References

Amabile, T.M., Hennessey, B.A., Grossman, B.S., 1986. Social influences on creativity: the effects of contracted-for reward. J. Personal. Soc. Psychol. 50 (1), 14–23. https://doi.org/10.1037/0022-3514.50.1.14.

Aston-Jones, G., Cohen, J.D., 2005. An integrative theory of locus coeruleus-norepinephrine function: Adaptive Gain and Optimal Performance. Annu. Rev. Neurosci. 28 (1), 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709.

Badcock, P.B., Friston, K.J., Ramstead, M.J.D., 2019. The hierarchically mechanistic mind: a free-energy formulation of the human psyche. Phys. Life Rev. 31, 104–121. https://doi.org/10.1016/j.plrev.2018.10.002.

Ball, L.J., Marsh, J.E., Litchfield, D., Cook, R.L., Booth, N., 2015. When distraction helps: evidence that concurrent articulation and irrelevant speech can facilitate insight problem solving. Think. Reason. 21 (1), 76–96.

Botvinick, M., Toussaint, M., 2012. Planning as inference. Trends in cognitive sciences 16 (10), 485–488.

Bouret, S., Sara, S.J., 2005. Network reset: a simplified overarching theory of locus coeruleus noradrenaline function. Trends Neurosci. 28 (11), 574–582. https://doi.org/10.1016/j.tins.2005.09.002.

Bowden, E., Jungbeeman, M., 2007. Methods for investigating the neural components of insight. Methods 42 (1), 87–99. https://doi.org/10.1016/j.ymeth.2006.11.007.

Bowden, E., Jungbeeman, M., Fleck, J., Kounios, J., 2005. New approaches to demystifying insight. Trends Cogn. Sci. 9 (7), 322–328. https://doi.org/10.1016/j.tics.2005.05.012.

Bowden, E.M., 1997. The effect of reportable and unreportable hints on anagram solution and the aha! experience. Conscious. Cogn. 6 (4), 545–573.

Bowers, K.S., Regehr, G., Balthazard, C., Parker, K., 1990. Intuition in the context of discovery. Cogn. Psychol. 22 (1), 72–110. https://doi.org/10.1016/0010-0285(90)90004-N.

Carhart-Harris, R.L., Friston, K.J., 2019. REBUS and the anarchic brain: toward a unified model of the brain action of psychedelics. Pharmacol. Rev. 71 (3), 316–344. https://doi.org/10.1124/pr.118.017160.

Chronicle, E.P., MacGregor, J.N., Ormerod, T.C., 2004. What makes an insight problem? the roles of heuristics, goal conception, and solution recoding in knowledge-lean problems. J. Exp. Psychol.: Learn., Mem., Cogn. 30 (1), 14–27. https://doi.org/10.1037/0278-7393.30.1.14.

Clark, A., 2013. Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behav. Brain Sci. 36 (3), 181–204. https://doi.org/10.1017/S0140525×12000477.

Corcoran, A.W., Pezzulo, G., Hohwy, J., 2020. From allostatic agents to counterfactual cognisers: active inference, biological regulation, and the origins of cognition. Biol. Philos. 35 (3), 1–45.

Cristofori, I., Salvi, C., Beeman, M., Grafman, J., 2018. The effects of expected reward on creative problem solving. Cogn. Affect. Behav. Neurosci. 18 (5), 925–931 doi: 10.3758/s13415-018-0613-5.

Cristofori, I., Salvi, C., Beeman, M., Grafman, J., 2018. The effects of expected reward on creative problem solving. Cogn., Affect., Behav. Neurosci. 18 (5), 925–931. https://doi.org/10.3758/s13415-018-0613-5.

Cushen, P.J., Wiley, J., 2012. Cues to solution, restructuring patterns, and reports of insight in creative problem solving. Conscious. Cogn. 21 (3), 1166–1175. https://doi.org/10.1016/j.concog.2012.03.013.

Damasio, A.R., 1996. The somatic marker hypothesis and the possible functions of the prefrontal cortex. Philos. Trans. R. Soc. Lond. Ser. B: Biol. Sci. 351 (1346), 1413–1420.

Danek, A.H., Salvi, C., 2018. Moment of truth: Why Aha! experiences are correct. J. Creat. Behav.

Danek, A.H., Wiley, J., 2017. What about false insights? deconstructing the Aha! Experience along its multiple dimensions for correct and incorrect solutions separately. Front. Psychol. 7, 2077.

Danek, A.H., Wiley, J., 2020. What causes the insight memory advantage? Cognition 205, 104411. https://doi.org/10.1016/j.cognition.2020.104411.

Danek, A.H., Fraps, T., von Müller, A., Grothe, B., Öllinger, M., 2013. Aha! experiences leave a mark: facilitated recall of insight solutions. Psychol. Res. 77 (5), 659–669. https://doi.org/10.1007/s00426-012-0454-8.

Danek, A.H., Fraps, T., von Müller, A., Grothe, B., Öllinger, M., 2014. Working wonders? investigating insight with magic tricks. Cognition 130 (2), 174–185. https://doi.org/10.1016/j.cognition.2013.11.003.

Devauges, V., Sara, S.J., 1990. Activation of the noradrenergic system facilitates an attentional shift in the rat. Behav. Brain Res. 39 (1), 19–28. https://doi.org/10.1016/0166-4328(90)90118-X.

Dietrich, A., Kanso, R., 2010. A review of EEG, ERP, and neuroimaging studies of creativity and insight. Psychol. Bull. 136 (5), 822–848. https://doi.org/10.1037/a0019749.

Dougal, S., Schooler, J.W., 2007. Discovery misattribution: when solving is confused with remembering. J. Exp. Psychol.: Gen. 136 (4), 577–592. https://doi.org/10.1037/0096-3445.136.4.577.

Dubey, R., Ho, M.K., Mehta, H., Griffiths, T., 2021. Aha! Moments Corresp. meta-Cogn. Predict. errors. PsyArXiv. https://doi.org/10.31234/osf.io/c5v42.

Engelhard, I.M., McNally, R.J., van Schie, K., 2019. Retrieving and modifying traumatic memories: recent research relevant to three controversies. Curr. Dir. Psychol. Sci. 28 (1), 91–96. https://doi.org/10.1177/0963721418807728.

Feldman, H., Friston, K., 2010. Attention, uncertainty, and free-energy. Front. Hum. Neurosci. 4, 215.

FitzGerald, T.H.B., Dolan, R.J., Friston, K., 2015. Dopamine, reward learning, and active inference. Front. Comput. Neurosci. 9, 136. https://doi.org/10.3389/fncom.2015.00136.

Fleck, J.I., Weisberg, R.W., 2013. Insight versus analysis: evidence for diverse methods in problem solving. J. Cogn. Psychol. 25 (4), 436–463. https://doi.org/10.1080/20445911.2013.779248.

Friston, K., 2008. Hierarchical models in the brain. PLoS Comput. Biol. 4 (11), e1000211 https://doi.org/10.1371/journal.pcbi.1000211.

Friston, K., 2010. The free-energy principle: a unified brain theory? Nat. Rev. Neurosci. 11 (2), 127–138. https://doi.org/10.1038/nrn2787.

Friston, K., Schwartenbeck, P., FitzGerald, T., Moutoussis, M., Behrens, T., Dolan, R.J., 2014. The anatomy of choice: dopamine and decision-making. Philos. Trans. R. Soc. B: Biol. Sci. 369 (1655), 20130481. https://doi.org/10.1098/rstb.2013.0481.

Friston, K., FitzGerald, T., Rigoli, F., Schwartenbeck, P., O'Doherty, J., Pezzulo, G., 2016a. Active inference and learning. Neurosci. Biobehav. Rev. 68, 862–879. https://doi.org/10.1016/j.neubiorev.2016.06.022.

Friston, K.J., Shiner, T., FitzGerald, T., Galea, J.M., Adams, R., Brown, H., Dolan, R.J., Moran, R., Stephan, K.E., Bestmann, S., 2012. Dopamine, affordance and active inference. PLOS Comput. Biol. 8 (1), e1002327 https://doi.org/10.1371/journal.pcbi.1002327.

Friston, K.J., Litvak, V., Oswal, A., Razi, A., Stephan, K.E., Van Wijk, B.C., Ziegler, G., Zeidman, P., 2016b. Bayesian model reduction and empirical Bayes for group (DCM) studies. Neuroimage 128, 413–431.

Friston, K.J., Lin, M., Frith, C.D., Pezzulo, G., Hobson, J.A., Ondobaka, S., 2017. Active inference, curiosity and insight. Neural Comput. 29 (10), 2633–2683. https://doi.org/10.1162/neco_a_00999.

Gable, S.L., Hopper, E.A., Schooler, J.W., 2019. When the muses strike: creative ideas of physicists and writers routinely occur during mind wandering. Psychol. Sci. 30 (3), 396–404. https://doi.org/10.1177/0956797618820626.

S. Gadsby J. Hohwy Why use predictive processing to explain psychopathology? The case of anorexia nervosa 2019 doi: 10.31234/osf.io/y46z5.

Garcia-Romeu, A., Davis, A.K., Erowid, F., Erowid, E., Griffiths, R.R., Johnson, M.W., 2019. Cessation and reduction in alcohol consumption and misuse after psychedelic use. J. Psychopharmacol. 33 (9), 1088–1101.

Garrido, M.I., Kilner, J.M., Stephan, K.E., Friston, K.J., 2009. The mismatch negativity: a review of underlying mechanisms. Clin. Neurophysiol. 120 (3), 453–463.

Gick, M.L., Lockhart, R.S., 1995. Cognitive and Affective Components of Insight. In The nature of insight. The MIT Press,, pp. 197–228.

Gigerenzer, G., Gaissmaier, W., 2011. Heuristic decision making. Annu. Rev. Psychol. 62 (1), 451–482. https://doi.org/10.1146/annurev-psych-120709-145346.

Gilhooly, K.J., Georgiou, G.J., Sirota, M., Paphiti-Galeano, A., 2019. Incubation and suppression processes in creative problem solving. In: *Insight and Creativity in Problem Solving*. Routledge, pp. 130–146.

Gilhooly, K., Murphy, P., 2005. Differentiating insight from non-insight problems. Think. Reason. 11 (3), 279–302. https://doi.org/10.1080/13546780442000187.

Grant, E.R., Spivey, M.J., 2003. Eye movements and problem solving: Guiding attention guides thought. Psychological Science 14 (5), 462–466. https://doi.org/10.1111/1467-9280.02454.

Grimmer, H.J., Laukkonen, R., Tangen, J., von Hippel, W., 2022a. Eliciting false insights with semantic priming. Psychon. Bull. Rev. 29 (3), 954–970.

Grimmer, H.J., Laukkonen, R.E., Freydenzon, A., von Hippel, W., Tangen, J.M., 2022b. Thinking style and psychosis proneness do not predict false insights. Conscious. Cogn. 104, 103384.

Grimmer, H.J., Tangen, J.M., Freydenzon, A., Laukkonen, R.E., 2023. The illusion of insight: detailed warnings reduce but do not prevent false "Aha!" moments. Cognition and Emotion 37 (2), 329–338. https://doi.org/10.31234/osf.io/shgfr.

Haarsma, J., Fletcher, P.C., Griffin, J.D., Taverne, H.J., Ziauddeen, H., Spencer, T.J., Miller, C., Katthagen, T., Goodyer, I., Diederen, K.M.J., Murray, G.K., 2021. Precision weighting of cortical unsigned prediction error signals benefits learning, is mediated by dopamine, and is impaired in psychosis. Mol. Psychiatry 26 (9), 5320–5333. https://doi.org/10.1038/s41380-020-0803-8.

Hattori, M., Sloman, S.A., Orita, R., 2013. Effects of subliminal hints on insight problem solving. Psychon. Bull. Rev. 20 (4), 790–797. https://doi.org/10.3758/s13423-013-0389-0.

Hedne, M.R., Norman, E., Metcalfe, J., 2016. Intuitive feelings of warmth and confidence in insight and noninsight problem solving of magic tricks. Front. Psychol. 7, 1314.

Hélie, S., Sun, R., 2010. Incubation, insight, and creative problem solving: a unified theory and a connectionist model. Psychol. Rev. 117 (3), 994–1024. https://doi.org/10.1037/a0019532.

Heng, Y.T., Barnes, C.M., Yam, K.C., 2023. Cannabis use does not increase actual creativity but biases evaluations of creativity (Apr). J. Appl. Psychol. 108 (4), 635–646. https://doi.org/10.1037/apl0000599. Epub 2022 Jul 28. PMID: 35901408.

Hertwig, R., Herzog, S.M., Schooler, L.J., Reimer, T., 2008. Fluency heuristic: A model of how the mind exploits a by-product of information retrieval. Journal of Experimental Psychology: Learning, memory, and cognition 34 (5), 1191.

Hobson, J.A., Friston, K.J., 2012. Waking and dreaming consciousness: neurobiological and functional considerations. Progress in neurobiology 98 (1), 82–98.

Hohwy, J., 2013. The predictive mind. Oxford University Press.

Holroyd, C.B., Coles, M.G.H., 2002. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. Psychol. Rev. 109 (4), 679–709. https://doi.org/10.1037/0033-295X.109.4.679.

James, W., 1979. The Will to Believe and Other Essays in Popular Philosophy. Harvard University Press.

Jarman, M.S., 2014. Quantifying the qualitative: measuring the insight experience. Creat. Res. J. 26 (3), 276–288. https://doi.org/10.1080/10400419.2014.929405.

Jennissen, S., Huber, J., Ehrenthal, J.C., Schauenburg, H., Dinger, U., 2018. Association between insight and outcome of psychotherapy: Systematic review and meta-analysis. Am. J. Psychiatry 175 (10), 961–969.

Jung-Beeman, M., Bowden, E.M., Haberman, J., Frymiare, J.L., Arambel-Liu, S., Greenblatt, R., Reber, P.J., Kounios, J., 2004. Neural activity when people solve verbal problems with insight. PLoS Biol. 2 (4), e97 https://doi.org/10.1371/journal.pbio.0020097.

Kahneman, D., 2011. Thinking, Fast and Slow. Macmillan.

Kizilirmak, J.M., Galvao Gomes da Silva, J., Imamoglu, F., Richardson-Klavehn, A., 2016. Generation and the subjective feeling of "aha!" are independently related to learning from insight. Psychol. Res. 80 (6), 1059–1074. https://doi.org/10.1007/s00426-015-0697-2.

Koriat, A., 1993. How do we know that we know? the accessibility model of the feeling of knowing. Psychol. Rev. 100 (4), 609–639. https://doi.org/10.1037/0033-295X.100.4.609.

Kounios, J., Beeman, M., 2009. The *Aha!* moment: the cognitive neuroscience of insight. Curr. Dir. Psychol. Sci. 18 (4), 210–216. https://doi.org/10.1111/j.1467-8721.2009.01638.x.

Kounios, J., Beeman, M., 2014. The cognitive neuroscience of insight. Annu. Rev. Psychol. 65 (1), 71–93. https://doi.org/10.1146/annurev-psych-010213-115154.

Kounios, J., Frymiare, J.L., Bowden, E.M., Fleck, J.I., Subramaniam, K., Parrish, T.B., Jung-Beeman, M., 2006. The prepared mind: neural activity prior to problem presentation predicts subsequent solution by sudden insight. Psychol. Sci. 17 (10), 882–890. https://doi.org/10.1111/j.1467-9280.2006.01798.x.

Kounios, J., Fleck, J.I., Green, D.L., Payne, L., Stevenson, J.L., Bowden, E.M., Jung-Beeman, M., 2008. The origins of insight in resting-state brain activity. Neuropsychologia 46 (1), 281–291. https://doi.org/10.1016/j.neuropsychologia.2007.07.013.

Lak, A., Nomoto, K., Keramati, M., Sakagami, M., Kepecs, A., 2017. Midbrain dopamine neurons signal belief in choice accuracy during a perceptual decision. Curr. Biol. 27 (6), 821–832.

Laukkonen, R.E., Sacchet, M.D., Barendregt, H., Devaney, K.J., Chowdhury, A., Slagter, H.A., 2023. Cessations of consciousness in meditation: Advancing a scientific understanding of nirodha samāpatti. Progress in Brain Research. https://doi.org/10.1016/bs.pbr.2022.12.007.

Laukkonen, R.E., Slagter, H.A., 2021. From many to (n) one: meditation and the plasticity of the predictive mind. Neurosci. Biobehav. Rev.

Laukkonen, R.E., Tangen, J.M., 2017. Can observing a Necker cube make you more insightful? Conscious. Cogn. 48, 198–211. https://doi.org/10.1016/j.concog.2016.11.011.

Laukkonen, R.E., Tangen, J.M., 2018. How to detect insight moments in problem solving experiments. Front. Psychol. 9, 282.

Laukkonen, R.E., Kaveladze, B.T., Tangen, J.M., Schooler, J.W., 2020. The dark side of Eureka: artificially induced Aha moments make facts feel true. Cognition 196, 104122.

Laukkonen, R.E., Ingledew, D.J., Grimmer, H.J., Schooler, J.W., Tangen, J.M., 2021. Getting a grip on insight: real-time and embodied Aha experiences predict correct solutions. Cogn. Emot. 0 (0), 1–18. https://doi.org/10.1080/02699931.2021.1908230.

Laukkonen, R.E., Kaveladze, B.T., Protzko, J., Tangen, J.M., von Hippel, W., Schooler, J. W., 2022. Irrelevant insights make worldviews ring true. Sci. Rep. 12 (1), 2075 https://doi.org/10.1038/s41598-022-05923-3.

Lawson, R.P., Rees, G., Friston, K.J., 2014. An aberrant precision account of autism. Front. Hum. Neurosci. 8, 302.

Lazer, D.M.J., Baum, M.A., Benkler, Y., Berinsky, A.J., Greenhill, K.M., Menczer, F., Metzger, M.J., Nyhan, B., Pennycook, G., Rothschild, D., Schudson, M., Sloman, S.A., Sunstein, C.R., Thorson, E.A., Watts, D.J., Zittrain, J.L., 2018. The science of fake news. Science 359 (6380), 1094–1096. https://doi.org/10.1126/science.aao2998.

Liljedahl, P.G., 2005. Mathematical discovery and affect: the effect of AHA! experiences on undergraduate mathematics students. Int. J. Math. Educ. Sci. Technol. 36 (2–3), 219–234.

Limanowski, J., Friston, K., 2018. Seeing the dark': grounding phenomenal transparency and opacity in precision estimation for active inference. Frontiers in psychology 9, 643.

MacGregor, J.N., Ormerod, T.C., Chronicle, E.P., 2001. Information processing and insight: a process model of performance on the nine-dot and related problems. J. Exp. Psychol.: Learn., Mem., Cogn. 27 (1), 176–201. https://doi.org/10.1037/0278-7393.27.1.176.

Mai, X., Luo, J., Wu, J., Luo, Y., 2004. "Aha!" effects in a guessing riddle task: an event-related potential study. Hum. Brain Mapp. 22 (4), 261–270.

Maier, N.R.F., 1931. Reasoning in humans. II. The solution of a problem and its appearance in consciousness. J. Comp. Psychol. 12 (2), 181–194. https://doi.org/10.1037/h0071361.

Mason, N.L., Kuypers, K.P.C., Reckweg, J.T., et al., 2021. Spontaneous and deliberate creative cognition during and after psilocybin exposure. Transl. Psychiatry 11, 209. https://doi.org/10.1038/s41398-021-01335-5.

McGaughy, J., Ross, R.S., Eichenbaum, H., 2008. Noradrenergic, but not cholinergic, deafferentation of prefrontal cortex impairs attentional set-shifting. Neuroscience 153 (1), 63–71. https://doi.org/10.1016/j.neuroscience.2008.01.064.

Metcalfe, J., Wiebe, D., 1987. Intuition in insight and noninsight problem solving. Mem. Cogn. 15 (3), 238–246. https://doi.org/10.3758/BF03197722.

Metcalfe, J., Schwartz, B.L., Joaquim, S.G., 1993. The cue-familiarity heuristic in metacognition. J. Exp. Psychol.: Learn., Mem., Cogn. 19 (4), 851–861. https://doi.org/10.1037/0278-7393.19.4.851.

Metzinger, T. , 2017. The Problem of Mental Action. In T. Metzinger & W. Wiese (Eds.), *Philosophy and Predicitive Processing.*

Näätänen, R., Alho, K., 1995. Mismatch negativity-a unique measure of sensory processing in audition. Int. J. Neurosci. 80 (1–4), 317–337.

Nasar, S., 2001. A Beautiful Mind: The Life of Mathematical Genius and Nobel Laureate John Nash. Simon and Schuster,.

Noorani, T., Garcia-Romeu, A., Swift, T.C., Griffiths, R.R., Johnson, M.W., 2018. Psychedelic therapy for smoking cessation: qualitative analysis of participant accounts. J. Psychopharmacol. 32 (7), 756–769.

Oh, Y., Chesebrough, C., Erickson, B., Zhang, F., Kounios, J., 2020. An insight-related neural reward signal. NeuroImage 214, 116757. https://doi.org/10.1016/j.neuroimage.2020.116757.

Ohlsson, S., 1984. Restructuring revisited.: I. Summary and critique of the Gestalt theory of problem solving. Scand. J. Psychol. 25 (1), 65–78. https://doi.org/10.1111/j.1467-9450.1984.tb01001.x.

Oudeyer, P.Y., Kaplan, F., Hafner, V.V., 2007. Intrinsic motivation systems for autonomous mental development. IEEE transactions on evolutionary computation 11 (2), 265–286.

Ovington, L.A., Saliba, A.J., Moran, C.C., Goldring, J., MacDonald, J.B., 2018. Do people really have insights in the shower? the when, where and who of the aha! moment. J. Creat. Behav. 52 (1), 21–34. https://doi.org/10.1002/jocb.126.

Parr, T., Friston, K.J., 2017. Working memory, attention, and salience in active inference. Scientific reports 7 (1), 14678. Chicago.

Qiu, J., Li, H., Luo, Y., Chen, A., Zhang, F., Zhang, J., Yang, J., Zhang, Q., 2006. Brain mechanism of cognitive conflict in a guessing Chinese logogriph task. Neuroreport 17 (6), 679–682.

Rao, R.P., Ballard, D.H., 1999. Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. Nat. Neurosci. 2 (1), 79–87.

Reber, R., Schwarz, N., 1999. Effects of perceptual fluency on judgments of truth. Conscious. Cogn. 8 (3), 338–342. https://doi.org/10.1006/ccog.1999.0386.

Reber, R., Winkielman, P., Schwarz, N., 1998. Effects of perceptual fluency on affective judgments. Psychol. Sci. 9 (1), 45–48. https://doi.org/10.1111/1467-9280.00008.

Roseman, L., Nutt, D.J., Carhart-Harris, R.L., 2018. Quality of acute psychedelic experience predicts therapeutic efficacy of psilocybin for treatment-resistant depression. Front. Pharmacol. 8, 974.

Salvi, C., Bowden, E.M., 2016. Looking for creativity: where do we look when we look for new ideas? Front. Psychol. 7 https://doi.org/10.3389/fpsyg.2016.00161.

Salvi, C., Bricolo, E., Franconeri, S.L., Kounios, J., Beeman, M., 2015. Sudden insight is associated with shutting out visual inputs. Psychon. Bull. Rev. 22 (6), 1814–1819. https://doi.org/10.3758/s13423-015-0845-0.

Salvi, C., Bricolo, E., Kounios, J., Bowden, E., Beeman, M., 2016. Insight solutions are correct more often than analytic solutions. Think. Reason. 22 (4), 443–460. https://doi.org/10.1080/13546783.2016.1141798.

Salvi, C., Simoncini, C., Grafman, J., Beeman, M., 2020. Oculometric signature of switch into awareness? pupil size predicts sudden insight whereas microsaccades predict problem-solving via analysis. NeuroImage 217, 116933. https://doi.org/10.1016/j.neuroimage.2020.116933.

Salvi, C., Beeman, M., Bikson, M., McKinley, R., Grafman, J., 2020. TDCS to the right anterior temporal lobe facilitates insight problem-solving. Sci. Rep. 10 (1), 946 https://doi.org/10.1038/s41598-020-57724-1.

Sandved-Smith, L., Hesp, C., Mattout, J., Friston, K., Lutz, A., Ramstead, M.J., 2021. Towards a computational phenomenology of mental action: modelling meta-awareness and attentional control with deep parametric active inference. Neurosci. Conscious. 2021 (1), niab018.

Schmidhuber, J., 2010. Formal theory of creativity, fun, and intrinsic motivation (1990–2010). IEEE transactions on autonomous mental development 2 (3), 230–247.

Schooler, J., Melcher, J., 1995. The ineffability of insight. In: Smith, S.M., Ward, T.B., Finke, R.A. (Eds.), The Creative Cognition Approach. MIT press, Cambridge MA, pp. 97–133.

Schooler, J.W., Ohlsson, S., Brooks, K., 1993. Thoughts beyond words: when language overshadows insight. J. Exp. Psychol.: Gen. 122 (2), 166.

Schooler, J.W., Smallwood, J., Christoff, K., Handy, T.C., Reichle, E.D., Sayette, M.A., 2011. Meta-awareness, perceptual decoupling and the wandering mind. Trends Cogn. Sci. 15 (7), 319–326.

Schultz, W., 2016. Dopamine reward prediction-error signalling: a two-component response. Nat. Rev. Neurosci. 17 (3), 183–195. https://doi.org/10.1038/nrn.2015.26.

Schunn, C.D., Dunbar, K., 1996. Priming, analogy, and awareness in complex reasoning. Mem. Cogn. 24 (3), 271–284. https://doi.org/10.3758/BF03213292.

Schwartenbeck, P., Passecker, J., Hauser, T.U., FitzGerald, T.H., Kronbichler, M., Friston, K.J., 2019. Computational mechanisms of curiosity and goal-directed exploration. ELife 8, e41703. https://doi.org/10.7554/eLife.41703.

Schwartz, B.L., Jemstedt, A., 2021. The Role of Fluency and Dysfluency in Metacognitive Experiences. In: Moraitou, D., Metallidou, P. (Eds.), Trends and Prospects in Metacognition Research across the Life Span: A Tribute to Anastasia Efklides. Springer International Publishing, pp. 25–40. https://doi.org/10.1007/978-3-030-51673-4_2.

Schwartz, B.L., Pournaghdali, A., 2020. Tip-of-the-tongue States: Past and Future. In Memory Quirks. Routledge,.

Schwarz, N., 2012. Feelings-as-Information Theory. In: Van Lange, P., Kruglanski, A., Higgins, E. (Eds.), Handbook of Theories of Social Psychology: Volume 1. SAGE Publications Ltd, pp. 289–308. https://doi.org/10.4135/9781446249215.n15.

Seth, A.K., 2013. Interoceptive inference, emotion, and the embodied self. Trends Cogn. Sci. 17 (11), 565–573. https://doi.org/10.1016/j.tics.2013.09.007.

Shen, W., Yuan, Y., Liu, C., Luo, J., 2016. In search of the ‘Aha!’ experience: elucidating the emotionality of insight problem-solving. Br. J. Psychol. 107 (2), 281–298. https://doi.org/10.1111/bjop.12142.

Shen, W., Tong, Y., Yuan, Y., Zhan, H., Liu, C., Luo, J., Cai, H., 2018. Feeling the insight: uncovering somatic markers of the “aha” experience. Appl. Psychophysiol. Biofeedback 43 (1), 13–21. https://doi.org/10.1007/s10484-017-9381-1.

Skaar, Ø.O., Reber, R., 2020. The phenomenology of Aha-experiences. Motiv. Sci. 6 (1), 49–60. https://doi.org/10.1037/mot0000138.

Skaar, Ø.O., Reber, R., 2021. Motivation through insight: the phenomenological correlates of insight and spatial ability tasks. J. Cogn. Psychol. 33 (6–7), 631–643. https://doi.org/10.1080/20445911.2020.1844721.

Slovic, P., Finucane, M.L., Peters, E., MacGregor, D.G., 2007. The affect heuristic. Eur. J. Oper. Res. 177 (3), 1333–1352.

Smith, R.W., Kounios, J., 1996. Sudden insight: all-or-none processing revealed by speed–accuracy decomposition. J. Exp. Psychol.: Learn., Mem., Cogn. 22 (6), 1443–1462. https://doi.org/10.1037/0278-7393.22.6.1443.

Sprugnoli, G., Rossi, S., Emmendorfer, A., Rossi, A., Liew, S.L., Tatti, E., Santarnecchi, E., 2017. Neural correlates of Eureka moment. Intelligence 62, 99–118.

Stuyck, H., Aben, B., Cleeremans, A., Van den Bussche, E., 2021. The Aha! moment: Is insight a different form of problem solving? Conscious. Cogn. 90 https://doi.org/10.1016/j.concog.2020.10305.

Subramaniam, K., Kounios, J., Parrish, T.B., Jung-Beeman, M., 2009. A brain mechanism for facilitation of insight by positive affect. J. Cogn. Neurosci. 21 (3), 415–432. https://doi.org/10.1162/jocn.2009.21057.

Suzuki, Y., Minami, T., Nakauchi, S., 2018. Association between pupil dilation and implicit processing prior to object recognition via insight. Sci. Rep. 8 (1), 6874.

Thagard, P., Stewart, T.C., 2011. The AHA! experience: creativity through emergent binding in neural networks. Cogn. Sci. 35 (1), 1–33. https://doi.org/10.1111/j.1551-6709.2010.01142.x.

Threadgold, E., Marsh, J.E., Ball, L.J., 2018. Normative data for 84 UK English rebus puzzles. Front. Psychol. 9, 2513.

Tik, M., Sladky, R., Luft, C.D.B., Willinger, D., Hoffmann, A., Banissy, M.J., Bhattacharya, J., Windischberger, C., 2018. Ultra-high-field fMRI insights on insight: Neural correlates of the Aha!-moment. Hum. Brain Mapp. 39 (8), 3241–3252. https://doi.org/10.1002/hbm.24073.

Timmermann, C., Kettner, H., Letheby, C., Roseman, L., Rosas, F.E., Carhart-Harris, R.L., 2021. Psychedelics alter metaphysical beliefs. Scientific reports 11 (1), 22166.

Tononi, G., Cirelli, C., 2006. Sleep function and synaptic homeostasis. Sleep. Med. Rev. 10 (1), 49–62.

Topolinski, S., Reber, R., 2010. Gaining Insight Into the “Aha” Experience. Curr. Dir. Psychol. Sci. 19 (6), 402–405. https://doi.org/10.1177/0963721410388803.

Topolinski, S., Strack, F., 2009. The architecture of intuition: fluency and affect determine intuitive judgments of semantic and visual coherence and judgments of grammaticality in artificial grammar learning. J. Exp. Psychol.: Gen. 138 (1), 39–63. https://doi.org/10.1037/a0014678.

Tulver, K., Kaup, K.K., Laukkonen, R., Aru, J. , 2023, Restructuring insight: An integrative review of insight in problem-solving, meditation, psychotherapy, delusions and psychedelics. Consciousness & Cognition, in Press. https://doi.org/10.31234/osf.io/8fbt9.

Tulver, K., Kaup, K.K., Laukkonen, R., Aru, J., 2023. Restructuring insight: An integrative review of insight in problem-solving, meditation, psychotherapy, delusions and psychedelics. Consciousness and cognition 110, 103494.

Tversky, A., Kahneman, D., 1974. Judgment under uncertainty: heuristics and biases. Science 185 (4157), 1124–1131. https://doi.org/10.1126/science.185.4157.1124.

Ueltzhöffer, K., 2018. Deep active inference. Biol. Cybern. 112 (6), 547–573.

Valueva, E., Lapteva, E., Ushakov, D., 2016. Aha-cueing in problem solving. Learn. Individ. Differ. 52, 204–208. https://doi.org/10.1016/j.lindif.2016.02.003.

Van Dam, N.T., van Vugt, M.K., Vago, D.R., Schmalzl, L., Saron, C.D., Olendzki, A., Meissner, T., Lazar, S.W., Kerr, C.E., Gorchov, J., Fox, K.C.R., Field, B.A., Britton, W. B., Brefczynski-Lewis, J.A., Meyer, D.E., 2018. Mind the hype: a critical evaluation and prescriptive agenda for research on mindfulness and meditation. Perspect. Psychol. Sci. 13 (1), 36–61. https://doi.org/10.1177/1745691617709589.

Vincent, P., Parr, T., Benrimoh, D., Friston, K.J., 2019. With an eye on uncertainty: modelling pupillary responses to environmental volatility. PLoS Comput. Biol. 15 (7), e1007126.

Watts, R., Day, C., Krzanowski, J., Nutt, D., Carhart-Harris, R., 2017. Patients’ accounts of increased “connectedness” and “acceptance” after psilocybin for treatment-resistant depression. Journal of humanistic psychology 57 (5), 520–564.

Webb, M.E., Laukkonen, R.E., Cropper, S.J., Little, D.R., 2021. Commentary: Moment of (perceived) truth: Exploring accuracy of Aha! experiences. The Journal of Creative Behavior 55 (2), 289–293.

Webb, M.E., Little, D.R., Cropper, S.J., 2016. Insight is not in the problem: investigating insight in problem solving across task types. Front. Psychol. 7, 1424.

Webb, M.E., Little, D.R., Cropper, Simon J., 2018. Once more with feeling: normative data for the aha experience in insight and noninsight problems. Behav. Res. Methods 50 (5), 2035–2056. https://doi.org/10.3758/s13428-017-0972-9.

Weisberg, R.W., 2013. On the “demystification” of insight: a critique of neuroimaging studies of insight. Creat. Res. J. 25 (1), 1–14.

Weisberg, R.W., Alba, J.W., 1981. An examination of the alleged role of" fixation" in the solution of several" insight" problems. J. Exp. Psychol.: Gen. 110 (2), 169.

White, H., 1988. Semantic priming of anagram solutions. Am. J. Psychol. 383–399.

Whittlesea, B.W.A., Williams, L.D., 2001. The discrepancy-attribution hypothesis: I. The heuristic basis of feelings and familiarity. J. Exp. Psychol.: Learn., Mem., Cogn. 27 (1), 3–13. https://doi.org/10.1037/0278-7393.27.1.3.

Whittlesea, B.W.A., Jacoby, L.L., Girard, K., 1990. Illusions of immediate memory: evidence of an attributional basis for feelings of familiarity and perceptual quality. J. Mem. Lang. 29 (6), 716–732. https://doi.org/10.1016/0749-596X(90)90045-2.

Whittlesea, B.W.A., Masson, M.E.J., Hughes, A.D., 2005. False memory following rapidly presented lists: the element of surprise. Psychol. Res. 69 (5), 420–430. https://doi.org/10.1007/s00426-005-0213-1.

Yaniv, I., Meyer, D.E., 1987. Activation and metacognition of inaccessible stored information: potential bases for incubation effects in problem solving. J. Exp. Psychol.: Learn., Mem., Cogn. 13 (2), 187.

Yu, A.J., Dayan, P., 2005. Uncertainty, neuromodulation, and attention. Neuron 46 (4), 681–692. https://doi.org/10.1016/j.neuron.2005.04.026.

Zander, T., Öllinger, M., Volz, K.G., 2016. Intuition and insight: two processes that build on each other or fundamentally differ? Front. Psychol. 7. ⟨https://www.frontiersin.org/articles/10.3389/fpsyg.2016.01395⟩.

Zedelius, C.M., Schooler, J.W., 2015. Mind wandering “Ahas” versus mindful reasoning: alternative routes to creative solutions. Front. Psychol. 6 https://doi.org/10.3389/fpsyg.2015.00834.

Zhang, Z., Lei, Y., Li, H., 2016. Approaching the distinction between intuition and insight. Front. Psychol. 7. ⟨https://www.frontiersin.org/articles/10.3389/fpsyg.2016.01195⟩.