communications psychology

A Nature Portfolio journal

Perspective

https://doi.org/10.1038/s44271-025-00209-6

Boredom signals deviation from a cognitive homeostatic set point

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Boredom is the feeling of wanting but failing to engage the mind and can be conceived as one among many signals of suboptimal utilization of cognitive and neural resources. Using homeostasis as an analogy, this perspective argues that boredom represents a signal indicating deviation from optimal engagement—that is, deviation from a cognitive homeostatic set point. Within this model, allostasis accounts for chronic boredom (i.e., trait boredom proneness), according to which faulty internal models are responsible for why the highly boredom prone may set unrealistic expectations for engagement. In other words, the model characterizes boredom as a dynamic response to both internal and external exigencies, leading to testable hypotheses for both the nature of the state and the trait disposition. Furthermore, this perspective presents the broader notion that humans strive to optimally engage with their environs to maintain a kind of cognitive homeostatic set-point.

Boredom is a disengaged state characterized by a failure to optimally engage cognitive resources[1]. That corresponding lack of engagement is subjectively unpleasant, with boredom commonly rated as negatively valenced[2,3] and associated with feelings of agitation and restlessness[4]. Functional accounts suggest that boredom arises when one is not adequately utilizing cognitive resources signaling the need to explore for a more satisfying outlet for action[5–14]. Boredom vanishes once an endeavor deemed worthy is found and cognitive engagement resumes. This engagement-disengagement cycle represents a kind of feedback loop[11] needed to maintain some optimal level of cognitive engagement. What determines optimal cognitive engagement likely depends on context, effort, motivation, meaning, goals, and environmental constraints, among other possibilities. While the extent of engagement may differ in degree (i.e., a person can be slightly, moderately, or fully engaged), the drive to be engaged fulfils a basic human need—to optimally deploy cognitive resources. By analogy, such a self-regulatory process shares commonalities with homeostatic systems, which strive to maintain the internal stability of an organism by adjusting to the fluctuations of the external environment[15]. We propose that people strive to maintain cognitive engagement within adaptative internal boundaries in response to external perturbations[16]. Through the establishment and maintenance of cognitive homeostasis, cognitive-affective resources are managed dynamically and responsively in light of both internal and external changes. In the model proposed here, the limits of a desired cognitive set-point have values that are flexible and context-dependent, and the feeling of boredom operates as just one of several self-regulatory signals indicative of a departure from the set-point.

Here we first describe how falling outside of one's cognitive homeostatic set-point is not only felt as unpleasant but is also detrimental to the organism in terms of performance and mental well-being. Next, we posit several signaling mechanisms that are activated when one is outside of either the lower or upper bounds of the cognitive set-point. These signals include, but are not limited to, boredom, effort and anxiety. We zero in on boredom as a signal of particular interest in light of the recent surge of research into this experience, and the considerable literature linking it to markers of inadequate cognitive utilization. We then situate our model of boredom as a marker of deviation from optimal cognitive utilization within the context of predictive coding, suggesting potential avenues for exploring the neural signature of cognitive engagement. Further, we explore the trait propensity to experience boredom as an indication of dysfunctional regulation of the cognitive set-point. The latter raises an intriguing distinction between homeostatic and allostatic regulatory mechanisms that provides a promising avenue for further research.

A crucial feature of our model—and one that we believe distinguishes it from extant models of boredom—is the involvement of allostatic processes. These processes play a triple role in our model. First, allostatic processes confer flexibility to the parameters of cognitive involvement and specifically, to what counts as an acceptable (or desired) range of cognitive engagement. Unlike traditional homeostatic mechanisms that rely on fixed (prior) values for regulating variables, allostatic processes allow for the possibility of

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change. In particular, the experiencing agent can adjust the zone of satisfactory cognitive engagement on the basis of past experiences and learning. Thus, the 'priors' of boredom—beliefs or expectations about the states that our bodies and mind should be in—can change over time.

Second, the inclusion of allostatic processes gives our model of boredom an anticipatory component so that it is not merely reactive. According to our model, boredom is not simply a state that contributes to the correction of a particular error (viz., the difference between actual cognitive engagement and desired one); it also functions proactively so that it can minimize this error. Insofar as allostasis involves the integration of previous experiences and learned expectations, the model predicts that agents can use past experiences of boredom to foresee situations in which boredom is likely to recur. The model thus renders boredom proactive: the agent's behavior is affected not only by current (occurrent) feelings of boredom but also by the expectation that such feelings may arise in the future.

Finally, the involvement of both allostatic and homeostatic processes allows us to make progress in understanding the complex relationship between state boredom and trait boredom (or boredom proneness). According to our model, it is not only a failure or the atypical workings of homeostatic processes that can lead to boredom proneness (e.g., an inability to properly monitor and then regulate current levels of cognitive engagement, or a hyperawareness of interoceptive signals) but also the effects of allostatic processes. For instance, the zone of optimal cognitive engagement may shift beyond what was previously considered the homeostatic range. Such a move can create higher (perhaps even unrealistic) demands for cognitive engagement, which in turn could lead to the more frequent experience of boredom. In other words, if the 'bar' for what counts as cognitively engaging is raised, then it would be harder for an individual to find tasks and situations that meet those elevated demands.

We believe that what we outline below distinguished this model of boredom from extant accounts that in part couch boredom as triggered by inadequate attentional engagement[11], or as a mismatch between the current activity and expected levels of either meaning or attentional engagement[12]. Our cognitive homeostatic/allostatic account more broadly explains both state and trait boredom within a predictive coding account that in turn has ramifications for other cognitive/affective experiences. That is, this model has broader implications for the regulation of cognitive and affective processes writ large.

Boredom—the suboptimal utilization of cognitive resources

Most definitions of boredom converge on a singular characterization: boredom denotes insufficient cognitive engagement, which is felt as unpleasant and is negatively valenced[1–3,8,11,17]. Casting boredom in information processing terms offers a useful model to explicate the distinct pathways to the lack of cognitive engagement characteristic of boredom[18]. Specifically, optimal engagement of cognitive resources depends not only on an agent's ability to extract signal from noise but also on their capacity to continuously engage with that signal. On the one hand, deriving meaning from a constantly changing or chaotic barrage of information may prove to be difficult or even impossible. In such circumstances, one will typically stop trying to make sense of the information or exit the process of meaning-making, resulting in suboptimal use of cognitive resources and boredom. On the other hand, when faced with monotonous circumstances, perhaps characterized by an overabundance of repetition, one's cognitive resources are underutilized as the meaning is immediately manifest and easily extracted due to the redundancy, ultimately leading to boredom[19].

Evidence supports the existence of these two routes to underutilization of cognitive resources: (i) feelings of boredom are experienced when information is so complex it becomes impenetrable[12,20,21], and (ii) boredom commonly arises in monotonous environs or when repetitive tasks require little from people as cognitive agents[22–24]. More specifically, Struk and colleagues[21] asked people to rate their feelings of control when playing rounds of the game of rock, paper, scissors against a computer opponent in which they either won or lost 100% of the time. Those who reported either high or low levels of perceived control also reported being most bored. Similarly, Westgate and Wilson[12] titrated levels of difficulty in a kind of air traffic control task and found that boredom was highest at the low and high ends of difficulty. While each of these examples only indirectly assesses cognitive engagement, they hint at the possibility that boredom arises from two routes to suboptimal utilization of cognitive resources.

Our proposed account of boredom as a signal of suboptimal utilization of cognitive resources is also consistent with evidence from educational psychology which indicates that both over- and underchallenging tasks that lack value are prime determinants of boredom[25,26]. Thus, when one falls outside of the cognitive utilization set-point—either because the environment is too stimulating, challenging, and varied, or because it is not sufficiently stimulating, challenging, and varied—the feeling of boredom (i.e., a signal of cognitive underutilization) arises and can regulate behavior.

It should be noted that boredom is not solely determined by environmental exigencies. The individual, through self-regulatory mechanisms, plays a role in how boredom unfolds. That is, being bored implies a strong desire to do something other than what one is doing. However, in-the-moment feelings of boredom represent an unsatiated motivational state—one wants something to engage with but doesn't want anything currently available[27,28]. It is also possible that when bored, one recognizes the will to be engaged but struggles to articulate what it is that would satisfy. Either way, our theory emphasizes this 'desire bind' as a key component of boredom: a state symptomatic of a suboptimal deployment of cognitive resources. Therefore, boredom involves a strong, even if inarticulate, desire for change to restore an optimal cognitive set-point.

This characterization of boredom makes an important distinction between optimal deployment of cognitive resources and the purported tendency for humans to be cognitive misers[29–31]. Past work has suggested that the preservation of resources prevails when engaging with the world, which seems to be in opposition to our claim that boredom drives people towards optimal resource use. This can be resolved in a number of ways. First, given the interplay between the twin drives of exploration and exploitation[7], resource deployment may function distinctly for each drive (see also Agrawal et al.,[32]). When exploiting known resources, using cognitive capacities sparingly is an efficient strategy to exploit without depletion. On the other hand, exploration requires a different approach, one that meets the exigencies of the task at hand in some optimal manner. Second, optimal engagement does not presuppose the exhaustion of available resources. It could in fact be optimal to be a miser. Finally, there are many activities that humans engage in that demand full exertion of available resources. People certainly do things that would seem to make little sense in the context of miserly deployment of resources. Why do people dance, play sports, make music, or build model cathedrals out of toothpicks? These activities do not agree with conserving cognitive energy or resources. A key distinction might be how the deployment of cognitive resources feels[33]. One may tend towards miserliness when the demands of the task engender a feeling of 'mental strain'[33]. But as the activities just listed suggest (sports, music, crafts), humans commonly engage in effortful tasks that they nevertheless experience as rewarding[34]. Such engagement may not feel effortful because the tasks themselves function well to optimally deploy cognitive resources. That is, there may be an important distinction to be had between some objective measure of effort and the subjective valence we attach to this (e.g., recent work has shown that those who report enjoying physical vs. mental activities—and vice versa—rate them as being less effortful)[35]. In a similar vein, as Halperin and Vigotsky[36] recently note, it is important to distinguish effort from perceived effort. For example, Halperin and Vigotsky[36] define effort as "energy utilized to perform an action" (p. 2021) and perceived effort as "the instantaneous experience of utilizing energy to perform an action" (p. 2025). This conceptual separation provides space for dissociations between "how hard the system is working" and our experience of "how hard the system is working" and, potentially, the valence attached to that experience. In addition, one could imagine situating, in this space, a context sensitive kind of homeostatic set-point for desired maximum amount of "energy" expenditure, where falling above this point is perceived as effortful. We return to this idea later on.

The costs of boredom

If boredom represents a deviation from an optimal cognitive set-point, then there ought to be negative consequences for falling outside that range. By analogy with homeostasis, a drop in core body temperature can become fatal to the organism if unaddressed. Does a deviation from an optimal cognitive set-point similarly have negative consequences that demand action? There is ample evidence that it does in terms of the raft of maladaptive behavioral and affective consequences that befall those in a bored state or the highly boredom prone[37].

Clear examples of negative consequences associated with the inability to avoid boredom can be found in research on boredom proneness and its relation to higher rates of depression and anxiety[38–40]. For the highly boredom prone, there are strong associations with increased drug and alcohol use and problem gambling[41–46]. Some epidemiological work even links chronic boredom to poor heart health[47] while job boredom is associated with dysfunctional activity of the autonomic nervous system, framing the experience as an occupational hazard[48]. This evidence implies that a persistent failure to maintain cognitive engagement within a healthy set-point has long-term consequences for well-being.

Boredom also has more near-term consequences as reflected in laboratory studies in which both state and trait boredom are associated with deficient performance on standard tasks of sustained attention[49,50]. In addition, self-report metrics link higher boredom proneness to increases in everyday attentional lapses (e.g., pouring orange juice on your cereal)[51,52]. In the current framework, performance decrements associated with boredom assume that the cognitive set-point is typically set to afford meeting the demands of one's current task. While not required for every task, a desire to feel efficacious would support the existence, at least in the aggregate, of a positive association between one's cognitive set-point and task demands. Accepting such an association allows the prediction that state boredom should signal a deviation from optimal engagement with the task at hand, explicitly linking boredom with performance decrements. It is plausible that this relation between boredom and attention functions in other, related ways. That is, poor attentional performance may reflect the fact that a boredom episode has arisen, or may reflect a response to being bored, directing attention elsewhere given the current task is unengaging[11]. Either way they are associated with deviation from optimal engagement.

A different way to understand performance decrements associated with boredom is that they arise as a result of attempts to restore optimal cognitive engagement. For example, boredom is associated with increased rates of mind-wandering[53]. While mind-wandering could help restore cognitive engagement to an appropriate level, the resultant diversion from the primary task will also lead to performance decrements on that task. This mechanism for understanding performance decrements may also provide a natural explanation for associations between boredom and increased risk-taking[54–57] (although see Yakobi et al.,[58]). Namely, action choices born of boredom may reflect searching for something different to engage with, even if it appears to be against one's longer-term self-interest[46,59–61]. Recent evidence does suggest that boredom prompts maladaptive action choices, from viewing more negatively valenced images[59] to engaging in sadistic behaviors[62]. That is, boredom, functioning as a signal of deviation from an optimal cognitive set-point, prompts a search for novelty in the hopes of finding an experience more cognitively engaging[5] even if, in some cases this search leads to maladaptive choices.

In sum, boredom indicates a departure from an optimal cognitive set-point. Departures from this set-point lead to negative consequences both in terms of task performance (e.g., poor attentional control) and mental well-being (e.g., higher rates of depression). Ultimately, residing at one's optimal cognitive set-point and engaging in adaptative remediation to deviations from the set-point are important for preventing a host of negative consequences that straying from that set-point may bring.

Signaling a deviation from the cognitive set-point

Beyond the subjective feeling of boredom, what might signal the deviation from a cognitive set-point? One possibility would be changes in arousal levels. On the one hand, when faced with monotony and/or redundancy, accompanying lowered arousal levels likely reflect low cognitive utilization. On the other hand, feeling overwhelmed by constantly changing environs or tasks beyond one's skill set may lead to elevated arousal. Both situations underline the fact that the relation between boredom and arousal is a contentious issue[4,11,63]. Should boredom be considered a high, low or mixed arousal experience? Self-report metrics indicate that people rate boredom to be a low arousal experience (e.g., Van Tilburg & Igou, 2012)[64], but psychophysiological metrics (e.g., heart rate, skin conductance levels) show mixed results, split almost perfectly between findings of high and low arousal[65–71]. One suggestion is that arousal should not be considered a key component of the definition of boredom[63]. While we agree with this stance, it does not preclude the possibility that changes in arousal are associated with deviation from an optimal cognitive engagement set-point. Thus, a direct relation between high and low arousal and boredom is unlikely. Instead, a relation between an arousal-based indicator of a deviation from a cognitive set-point and boredom should be expected. To test these notions, experiments would need to capture continuous psychophysiological data associated with self-report metrics. While challenging, this is not impossible[72]. Recent work did just that using changes in various heart rate metrics to trigger self-report prompts. Results showed no clear evidence for discriminable psychophysiological signatures, or so-called fingerprints of affective experiences[72]. However, studies like this one do confirm the capacity to track the dynamics of psychophysiological experiences over time to associate those dynamics with both discrete affective episodes and chronic dispositions. This method could be used to examine not only the specific deviations from the cognitive set-point of interest (i.e., episodes of boredom), but also any occurrences of optimal cognitive engagement.

Cognitive failure is another plausible signal of deviation from an optimal cognitive set-point. That is, recognition, either implicitly or explicitly, that one has erred on a task may be enough to indicate a more general deviation from optimal engagement[73,74]. The suggestion here is that dynamic changes in arousal, errors in performance and other more "cognitive" appraisals of one's circumstances may all be associated with deviation from optimal engagement. Given our claim that boredom belongs to this category, we should expect associations between these signals and boredom. As outlined above, research suggests that both changes in arousal levels (whether elevated or lowered) and failures of attention are associated with post-task ratings of boredom[49,65] (see also Yakobi et al.,[58] Yakobi & Danckert, 2021[58,75] for similar findings correlating differences in ERPs with pre- and post-task boredom ratings).

As noted briefly above, feelings of effort (or perceived effort) may be another signal of deviance from a cognitive set-point to consider[34,76]. Effort has long proved a hard nut to crack both in terms of cognitive mechanistic accounts and the search for an associated physiological signature[76]. In general, humans appear averse to the experience of effort (e.g., Kool et al.[77] Westbrook & Braver, 2015[77,78]; see the discussion of cognitive misers above) though there may be exceptions to this idea (e.g., Inzlicht et al.,[34]). Like boredom, effort is generally negatively valenced and when presented with options one often "satisfices"—choosing the option that leads to a "good enough" solution—as opposed to striving for some maximal performance[77,79]. One recent theory of effort regulation cast it in terms of opportunity costs[76]. Specifically, any given action comes with the cost of foregoing potentially higher rewards inherent to alternate (but often unknown) options[80,81]. From this perspective, the rising experience of effort on a given task is a product of rising opportunity costs[76]. Similarly, the Expected Value of Control Theory[82] suggests a balance-seeking mechanism that employs feelings of cognitive effort to evaluate the potential cost of allocating resources to the task at hand. On both accounts, arguably, feelings of effort are a product on a computation over the moment-by-moment deployment of cognitive resources. It is worth pointing out here that we use the term cognitive resource to refer broadly to something that can be used to complete cognitive activities, rather than some internal limited supply that is consumed by (possibly depleted by) particular classes of cognitive acts[36,83]. Within the analogy of homeostasis offered here, perceived effort may emerge at the upper bounds of a cognitive set-point where cognitive capacity is overtaxed (e.g., the opportunity costs have become too great, the cost-benefit balance tipped too far on the cost side).

Feelings of effort and boredom are commonly correlated[84–86]. This relation brings us back to the information processing account that suggests boredom arises when information gain is either non-existent (i.e., redundancy is high) or impossible (i.e., high levels of noise, making signal detection overly challenging)[18]. Both cases lead to cognitive disengagement. In this framework, effort—when termed as processing complexity as opposed to compensatory control—would track closely with boredom. When things are redundant and monotonous, they likely feel boring and underchallenging—in other words, low in effort. When information gain is precluded, feelings of effort will be high, at least while one attempts to get an intellectual foothold to become engaged. If unsuccessful, boredom will ensue[20]. Therefore, boredom and effort might both signal a deviation from an ideal zone of cognitive engagement. This notion fits well with recent work suggesting that feelings of effort (i.e., effortful control) and/or the regulation of self-control are strongly related to feelings of boredom[6,14] (see Wolff et al.,[13] for a comprehensive review of this model).

One recent computational account of cognitive control suggests different functional properties for boredom and effort[32]. In this model, boredom prompts exploration only when information is redundant (and presumably effort is low). In contrast, rising feelings of effort prompt the system to retreat into behaviors that test the veracity of already established mental models[32]. That is, rising feelings of effort push the agent away from the uncertainty of exploratory behaviors and toward the familiarity of established models of how the world typically functions. In a sense then, this model deals with the action outcomes of feelings of boredom and effort—how people typically might respond to the different states—and not the broader conception proposed here, that both effort and boredom function to indicate to the organism a deviation from an optimal set-point.

In addition, it is possible to be in a low effort condition without experiencing boredom. Relaxation comes to mind (or daydreaming, or fantasizing)[87]. It is difficult to imagine a circumstance in which relaxation feels effortful. And yet, being relaxed is antithetical to being bored, suggesting that boredom and effort do not track perfectly together. Similarly, people can find themselves in highly effortful situations (e.g., learning a new skill) and nevertheless persist if they deem it to be intrinsically motivating. Things that are intrinsically motivating are also clearly rich in meaning, raising the possibility of yet another signal of deviation from a cognitive set-point; changes in situational meaning from one moment to the next may function as implicit cues that engagement is no longer optimal. What this exploration of effort regulation suggests is that, like the signals of homeostasis (and the various neuromodulatory systems briefly touched on later), these numerous signals of deviation from a cognitive set-point—boredom, effort, meaning, intrinsic motivation—likely interact in complex ways to maintain engagement.

What about signals indicating that engagement within an optimal cognitive set-point has been achieved? Curiosity, interest, and fluency may signal effective engagement and promote goal persistence[88]. In some sense, any experience that draws on curiosity, interest or fluency, could be said to be indicative of living at the upper bounds of the cognitive set-point—fully engaged in a task that is intrinsically motivating. As mentioned above, relaxation (when successful) may also indicate engagement within an optimal set-point—in this instance at the lower bounds of the range—experiencing little effort, not bored, but with no desire for increased cognitive engagement. Finally, the state of flow may represent a narrowing of the range that defines the cognitive set-point. It is worth noting, that the state of flow involves the experience of a very specific confluence of no fewer than nine factors[89,90]. Despite this, the concept has been criticized as being underspecified in theory[91,92]. This highlights that these distinct experiences of optimal engagement (including flow) pose difficult experimental challenges. First, variables (and their upper and lower bounds) indicative of performing within or deviating from the optimal cognitive set-point would need to be characterized. Whether these are derived from task performance (e.g., errors on sustained attention tasks), self-reports (e.g., probes triggered by changes in other variables), physiological metrics (e.g., HR, SCL, pupillometry), or more likely some combination of these, is yet to be determined. As with biological processes of homeostasis, the conceptualization here is not intended to suggest all signals of deviation from optimal are the same, but rather that they share a functional goal—to return the system to an optimal range of engagement.

Homeostasis and allostasis—reactive and predictive maintenance of cognitive engagement

Homeostasis is classically defined as a mechanism aimed at regulating physiological parameters (e.g., heart rate, blood pressure, temperature) within a range of values (the so-called set-point) to ensure viability of the organism[93]. In this sense, homeostatic mechanisms can be considered reactive since the perturbations of the physiological system that push parameters outside the set-point represent the data used to engage corrective responses intended to preserve values optimal for survival[94,95]. On the other hand, allostatic mechanisms are predictive. Forward models in the brain anticipate the outcomes of action choices and utilize prediction errors to alter future behaviors, all in the service of the same goal as homeostatic mechanisms—viability of the organism[94]. It is likely the case that both homeostatic and allostatic mechanisms are needed for flexible control of behavior[94]. Not all circumstances lend themselves to sensible predictions, thus requiring a good deal of reactive responding. Similarly, behavior would be inordinately susceptible to varying contexts were humans to rely solely on reactive processing.

In suggesting that boredom arises when there is a failure to engage cognitive resources, we are casting the signal in a reactive sense—closer to homeostasis than allostasis. That is, in-the-moment feelings of boredom may engage a kind of homeostatic correction by reacting to unanticipated external exigencies (e.g., monotony) that pushed us away from the set-point that represents cognitive engagement. In contrast, predictive allostatic processes may provide insights into understanding trait boredom proneness. That is, faulty predictive mechanisms, deficits in comparator processes contrasting expected and actual levels of engagement, or both, may underlie the highly boredom prone individual's challenges in instigating or maintaining optimal levels of cognitive engagement[6,8,13,14].

Research could address hypotheses regarding homeostatic responses to perturbations from an optimal cognitive engagement set-point by using continuous measures of physiological data associated with either task performance, on the one hand, or thought probes/affective state prompts, on the other[72]. Such an approach would not determine the psychophysiological fingerprint of either boredom or cognitive engagement (as there may not be such a signature). It would rather seek to determine inflection points, namely the appropriate metrics (e.g., HR, pre-ejection phase, heart rate variability, skin conductance, pupillometry, etc.) that reliably signal deviation from an optimal engagement set-point. Note that other measurable behaviors such as eye movements, fidgeting, and even facial expressions, may prove useful in determining what signals the onset of a boredom episode specifically, or a deviation from optimal engagement more broadly[96].

As outlined above, homeostasis reflects a reactive mechanism for maintaining physiological conditions that promote survival of the organism[95]. A common example would be the sleep-wake dependent homeostatic process that regulates human rest[97]. Using late-night drowsy driving as a relatable context, vigilance decrement is among the many signals of fatigue associated with the need to rest[98]. When examining boredom through the lens of the homeostatic circuit our model suggests, this state would be a signal (among other possible signals) associated with a drive to restore optimal engagement. A more recent model of affective regulation suggests that allostatic regulation of emotions operates in the service of predictive resource allocation[99–101]. This is an active inference account that proposes that interoceptive sensations are predicted by an internal model that anticipates the outcomes of actions, choosing specific courses of action to maintain an optimal physiological regulatory set-point for the organism

—i.e., allostasis[100]. A key theoretical difference between homeostasis and allostasis is that the latter, which literally means "stability through change"[95], involves regulated variables that are not fixed[94,102]. Therefore, the "desired" or "set" range of values for the regulated variable can and should change to better support the regulatory goal of engagement. In the context of the model of affect regulation briefly outline above, chronic boredom may arise due to a faulty internal model (i.e., inefficient representation of cognitive needs), or elevated prediction error (i.e., the expected reward values of actions are unrealistic), or some combination of both[8].

Our model is distinct from previous accounts in that it accommodates both homeostatic and allostatic perspectives when generating hypotheses that boredom functions as a deviation signal from an optimal cognitive set-point. Computational models could directly examine these assumptions. If boredom arises when cognitive resources are not engaged, a homeostatic mechanism may capture more accurately the role of in-the-moment feelings of boredom in maintaining a cognitive set-point. In this case, any action taken to redress deviation from an optimal set-point is first engaged as a reaction to rising feelings of boredom. Testing allostatic models in the context of dispositional differences in trait boredom proneness would also be informative since internal mental models are built over long-time scales—an individual's lifetime in many instances. Therefore, the mental models of those chronically prone to boredom may not accurately represent their needs based on prior experiences. Consistent failures to engage meaningfully with the world may have established an unrealistic cognitive set-point. Stuck in an updating loop that discounts the effectiveness of any possibilities present in the environment, the faulty model is consolidated, and boredom is perpetuated. This may arise for several reasons, for example through the setting of a range for engagement that is impossibly narrow (i.e., a Goldilocks zone for engagement that demands very specific conditions), or unrealistic expectations of reward values. For example, research has consistently shown a correlation between boredom proneness and higher levels of sensation seeking[56,103,104]. This relation may reflect a faulty internal representation of needs for optimal engagement that ultimately leads to a vicious cycle: the highly boredom prone individual seeks increased stimulation to eliminate their boredom, few options for engagement satisfy the inappropriately high threshold set for engagement, and boredom ensues.

Additional hypotheses can be derived from recent work showing that the boredom prone tend to be hyperaware of interoceptive signals while simultaneously struggling to make sense of those signals[105]. Given the claim that interoception may rely more on model predictions than on prediction error[106], we suggest that it may be the case that people who are highly prone to boredom have poor model-based predictions. In addition, in view of the suggestion from Feldman and colleagues (2024)[106] that interoception is dependent more on fluctuations in arousal levels than on cognitively determined ratings of valence, we propose that boredom and boredom proneness may be more strongly modulated by changes in arousal than by differences in how an event or task is rated in terms of valence. Claims of this kind are challenging to test in the lab but would be amenable to computational approaches.

Searching for a set-point in the brain

What might the neural signal of being within an optimal cognitive set-point look like? In essence, the past few decades of functional neuroimaging work could be cast as a vast endeavor to address that very question. When we examine the neural correlates of x—whether x is attention or working memory or empathy—we assume that the participants we scan are, at the very least, attempting to effectively utilize their cognitive resources to complete the task at hand. There are several problems with this assumption. First, the tasks we typically use to explore cognition and affect are generally uninteresting and repetitive. Thus, participants in experimental tasks may be routinely underutilizing cognitive resources. Second, while researchers often assume their definitions of concepts and domains are clear, these are often misconstrued—one neuroscientist's working memory is another's attention or worse, one neuroscientist's working memory is defined in demonstrably distinct ways from another's—a problem of ontology[107]. Thus, operationalizing the underutilization of cognitive resources as a deviation from an optimal cognitive set-point is a considerable challenge. Finally, the design of most neuroimaging work of the past three decades rests on subtraction logic. Therefore, we are bound to find distinct neural networks when examining any definition chosen for attention, working memory or any other cognitive-affective domain, despite the fact that all instances may reflect varying degrees of cognitive utilization. What is needed here is not simply to image the engaged brain, but to imagine first what it might look like.

Focusing on the disengaged brain could be a worthy starting point, by exploring the neural networks associated with being bored, or with mind-wandering, or any state in which engagement is clearly suboptimal[108–114] (see Drody et al.,[115] for review of imaging work on boredom). There is scant work examining the neural correlates of boredom, much of which confirms the association between boredom and failures of attention[58,75]. Contrasting the state of boredom with either flow[114] or interest[111] highlights default mode activation in the bored state, but what this network of brain regions represents exactly is not entirely clear. It is conceivable, for instance, that the default mode is activated when one is engaged in prospective planning, nostalgic reverie or other forms of self-referential thought[116]. Boredom is certainly a self-referential experience; "I am bored." So, what this default mode activity represents may not be disengagement, or a failure to optimally deploy cognitive resources, so much as it is a self-focused thought, rumination of a sort on the feeling of being bored[117]. Higher temporal resolution imaging of these subjective states will be needed to determine clearer neural signatures. It may also prove fruitful to design imaging experiments that track fluctuations in the experience of boredom as opposed to aggregating data from a single 'episode'. Such work is undoubtedly challenging from a methodological perspective[72], particularly for methods such as fMRI that have poor temporal resolution. Here we can turn to EEG to test notions of deviation from an optimal set-point to explore the dynamics not just of boredom, but of the notion of cognitive homeostasis writ large.

Resting state scans and asymmetries in EEG power may also tell us something about the unengaged brain (and by extension what neural activity would reflect being within a cognitive set-point). Recent work demonstrated an asymmetry in frontal alpha associated with boredom susceptibility[118], and a negative correlation between trait boredom proneness and power in both the alpha and theta spectra[58]. Interrogating EEG data in this manner may prove useful in characterizing dispositional propensities for engagement. What is needed are large data sets with multiple task environments to determine not what is uniquely associated with a given task, but rather what is common across multiple sensory domains and different goals. The question being asked is not what specific brain regions constitute optimal utilization of cognitive resources, but rather, what do the neural dynamics of being within that set-point across a broad range of domains present as in fMRI, EEG, etc.?

One promising analysis technique along these lines is network topology[119]. Where traditional analyses examine any regions of activation using subtraction logic, or functional connectivity—essentially exploring the correlations between regions of activation in a given task—network topology does not focus on which brain regions are activated but rather examines the extent to which activation is integrated across the whole brain[119,120].

While it is beyond the scope of this paper to fully examine this account of brain activity (see Shine[120] for review), it is worth a cursory examination to explore how it might inform the drive to maintain a cognitive set-point. For simple tasks that do not require complex cognitive resources (e.g., simple motor and sensory tasks) network topology is more segregated, perhaps reflective of the low demands of the task. With more complex tasks, for example, n-back working memory tasks, the topology becomes more integrated. The suggestion here is not that either a segregated or integrated brain state reflects an optimal cognitive set-point, but rather that the demands of any given context will determine the extent to which the brain ought to be segregated or integrated[120]. While the cholinergic system may promote segregation given associations with serotonin and selective attention[121,122], the noradrenergic system may promote integration given associations with exploratory behavior[123]. In other words, both neuromodulatory systems could be said to promote cognitive homeostasis in distinct ways.

Interestingly, recent work suggests that hallucinations in patients with Parkinson's Disease (PD) are associated with greater between-node activation, or more specifically, greater network integration[124]. The importance of this finding here is that it shows that there is indeed a dysfunction at some upper bound of network integration. In other words, more integration is not ubiquitously desired. Instead, some optimal level of integration (and, by inference, segregation in other circumstances) is needed, dependent on the task and goal contexts.

An important point here is that the neuromodulatory systems briefly discussed above (and others not mentioned) do not work in isolation. They rather form a coordinated response to changing sensory inputs, current goals, and motivational/affective states by striking a balance between segregated and integrated network states[120]. Each of these ascending neuromodulatory systems in turn receives descending input from particular brain regions. Descending projections to the cholinergic system from the paralimbic and frontopolar regions may facilitate segregation and be important for tasks in which greater focus of resources are required. Dysregulation of this interplay may present as a failure to sustain attention on a task—a common driver of boredom[49,50]. Alternatively, the noradrenergic system receives descending inputs from the dorsolateral prefrontal cortex and anterior cingulate, regions commonly involved in complex cognitive tasks and exploratory behaviors[125,126]. Again, dysregulation within this system may be felt as boredom; a failure to satisfy the desire to be engaged in meaningful goal pursuit[1,33]. This systems neuroscience approach offers an objective characterization of large-scale brain activity associated with a broad range of task conditions and affective responses enabling the objective testing of the proposal that humans seek a cognitive set-point.

Conclusion

Boredom is a ubiquitous human experience, one that has been shown to be on the rise in teenagers over the past decade or so[127]. The disposition to experience boredom frequently and intensely is consequential, with a long list of negative outcomes and maladaptive behaviors associated with boredom proneness[128]. Models of boredom have focused on isolated domains to explain the experience, ranging from attentional challenges[1,11], to novelty seeking[5], and meaning making[12,64,129]. More recently, the need for agency has been proposed as an overarching framework for understanding trait boredom proneness[27,33,130]. Functional accounts that cast boredom as a call to action provide a broad framework for bringing together these disparate facets of the experience, but do not provide a mechanism for how boredom might lead to action[8]. What we have proposed here casts the state and trait within a motivational framework, such that boredom signals the need to maintain an optimal level of engagement of one's cognitive resources. For the state, future research endeavors could explore whether boredom operates in the same manner at both the upper and lower bounds of a purported cognitive set-point. Do other signals of deviation from optimal deployment of cognitive resources—rising feelings of effort, frustration, or anxiety as just some examples—have differential or additive effects with feelings of boredom? For the trait disposition, do the highly boredom prone set unrealistic boundaries on what constitutes optimal engagement? This possibility is particularly intriguing in the context of boredom interventions: can inappropriate expectations for engagement be reset for the highly boredom prone? Alternatively, do the highly boredom prone struggle to accurately monitor ongoing behavior and to flexibly adjust both expectations for engagement and decisions related to coping with boredom? What does the neural signature of both boredom and optimal deployment of cognitive resources look like? All these questions become feasible within the context of a drive to maintain some form of cognitive homeostasis wherein resource allocation is driven to enable optimal engagement. As such, our model has wide ranging implications not only for boredom, but for cognitive-affective self-regulatory challenges more broadly. Moving forward, it will be important to determine whether there are multiple independent set-points critical for regulating thought, behaviour and affect, or whether a singular set-point exists with varied factors that determine how we remain within that optimal zone.

Received: 27 August 2024; Accepted: 31 January 2025;

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Acknowledgements

This work was supported by Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery grants to JD (#10762), EFR (#04091), as well as a Canada Research Chair to EFR (#950-232147). The funders had no role in the preparation of the manuscript or decision to publish.

Author contributions

J.D. and C.T. originally conceived of the paper and wrote the first draft. E.R., J.E., W.V-.T., A.E. all contributed to the development of the ideas represented here, to editing and writing drafts after the first draft.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44271-025-00209-6.

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Peer review information *Communications Psychology* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editor: Jennifer Bellingtier. A peer review file is available.