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Effort and boredom shape our experience of time

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ABSTRACT

Situations change over time, and so does our experience of them. For example, a task may initially feel engaging but can, over time, become monotonous and boring. Similarly, as processing demands increase or one's momentary capabilities decline, the same task can feel more or less effortful. The dynamics of these task-induced sensations matter because boredom and perceived effort shape behavior by driving optimization of resource utilization. Time is among the most fundamental resources to which people tend to be acutely sensitive across contexts. Here, we propose that the sensations of boredom and effort influence how the passing of time is experienced. Specifically, both states are linked to changes in interoception—the perception of internal bodily signals—which is known to play a key role in time perception. This proposal offers a framework for understanding how fundamental regulatory sensations, such as boredom and effort, shape temporal experience through interoceptive mechanisms. We highlight the insular cortex as a potential hub mediating the effects of interoceptive signals on time perception, integrating feelings of boredom and effort, and their influence on the experience of time.

Situations change over time. Novel tasks or situations can be loaded with processing demands and require significant effort. With increasing exposure and repetition they can feel void of meaningful events, generating the feeling of boredom (Wolff and Martarelli, 2020). Crucially, both sensations—effort and boredom—are powerful modulators of human behavior (Agrawal et al., 2022; Bieleke and Wolff, 2021; Shenhav et al., 2017; Székely and Michael, 2021; Wolff and Martarelli, 2020). Reward-based choice models of human behavior posit that both sensations are taken into account when people try to orient their behavior in an attempt to preserve limited resources (Brinkmann et al., 2021; Shenhav et al., 2013; Silvestrini et al., 2023; Wolff & Martarelli, 2020). From a computational perspective, effort and boredom are understood to act as dynamic cost-monitoring signals. Effort tracks one's momentary and cumulative action costs, whereas boredom serves as a meter indicating the degree to which one's current engagement generates too little informational or reward value (Darling, 2023; Gomez-Ramirez and Costa, 2017; Wolff and Martarelli, 2020; Xu et al., 2024).[1] Thus, effort and boredom inform us about the opportunity costs of our current action, indicating that persisting in the present activity may come at the expense of better alternatives (Agrawal et al., 2022; Schulze et al., 2025; Shenhav et al., 2013). One fundamental resource that people tend to be particularly sensitive to is time (Campbell and Seneca, 2004; Grüne-Yanoff, 2015; Klein-Flügge et al., 2015; Small, 2012; C.-X. Zhao et al., 2015). Whenever we feel that we are not getting much out of the time we spend doing something, we feel that time is dragging on, increasing the opportunity costs that are associated with this action. This can, for example, be the case if an activity is exceedingly hard or excessively boring. Here, we suggest that the perception of effort and boredom dynamically affect how the passing of time is experienced. More specifically, we draw from research on time perception, effort, and

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[1] This perspective aligns with the informational theory of flow (Melnikoff et al., 2022), which posits that subjective engagement depends on the mutual information between means (actions) and ends (outcomes). When effortful tasks reliably produce meaningful outcomes (high mutual information), they can promote flow; when repeated or overly predictable tasks provide little information about outcomes (low mutual information), they elicit boredom. In this sense, effort and boredom can be seen as modulators of the means/ends connection.

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boredom to make the case that effort and boredom increase awareness of bodily states, which in turn makes time seem to pass more slowly.

Imagine yourself sitting in front of your computer. You are tasked with rapidly categorizing words according to the color they are presented in. Sometimes the presented color and the meaning are congruent (the word green written in green color) and sometimes they are incongruent (the word green written in red color; i.e., the classic Stroop task) (Stroop, 1935). You know you will do this task for one hour with a small break every 5-minutes. In the beginning the task demands all your attention: Successive words seem to blur into each other, creating a seemingly constant stream of information and you have your hands full to correctly categorize the color of the words. The attentional demands of the task feel a bit overwhelming, and you wonder why it takes so long until the first break relieves you from the task. This was hard, you feel mentally drained, and although you know it was only five minutes, it felt much longer. In the next block, the task begins to feel easier, and the words do not seem to appear so rapidly after one another, making categorization a bit easier. You are absorbed by the task, and you are surprised that the second five minutes pass so quickly. After 50 min, it feels as if the duration the words are presented in has been shortened even further, and as if the empty time between successive presentations has been extended. Your attention starts to shift—you start to notice that the chair you are sitting on is slightly too low and you notice that your thoughts are drifting elsewhere. You also notice that you have started to commit more errors when categorizing the presented words. In your mind, you begin to explore other thoughts, sensations, observations. The last five minutes seem to drag on forever and you feel bored to death.

As this thought experiment illustrates, the very same sensory input—and rules on how to act upon this input - can create strikingly different feelings: As a function of one's familiarity with the input, perceptions of high effort and/or perceptions of high boredom might arise. Interestingly, the same sensory input can also feel as if it lasted longer or shorter. In the beginning, when processing the presented words required the most effort, stimulus duration felt longer and the 'empty time' (Zakay and Block, 1994) between successive presentations felt short. Conversely, when the person becomes bored, the stimulus presentation felt short and the empty time felt long. Importantly, in both scenarios the total duration of each five-minute block felt longer than in the middle of the task. This begs the question, why does subjective duration dynamically change, and how do effort and boredom affect the subjective shrinking or expansion of time?

Before we address these questions, we will briefly define key terms from research on time, explain how we use them in the present paper, and cover how they relate to boredom and effort. We will then describe pacemaker-accumulator models as a general cognitive framework for studying the perception of time and highlight how boredom and effort can affect time perception according to these models. We next turn to the putative mechanisms that explain how boredom and effort relate to time perception. To conclude, we will draw from neuroscientific research on boredom, effort, time perception and interoception, to suggest the insular cortex as a key junction that links boredom, effort and the perception of time.

1. Temporal dynamics of 'empty time' and 'loaded time'

Time perception refers to the degree of agreement between objective and subjective time (Fabbri et al., 2020). For example, how accurately one can guess the minutes one has waited in a room (Martarelli et al., 2024; Witowska et al., 2020) or how long one was cycling on an ergometer (Edwards and McCormick, 2017; Moore and Olson, 2022; Schütz et al., 2023). In turn, time perception can be more or less accurate, and people integrate various bits of information or situational knowledge to assess this. For example, I *know*, writing this paragraph cannot have exceeded one hour, because I have started writing about an hour before lunch break, and so far, no one has knocked to let me know it is lunch time. Time awareness on the other hand refers to 'the subjective impression of time passing quickly or slowly' (Fabbri et al., 2020, p. 2). So, in contrast to time perception, time awareness does not focus on how long something actually took, but how long it felt. For example, I *think* writing this paragraph took me almost one hour, but this hour *felt* like it took forever. In turn, time awareness is inherently about the subjective experience of the passage of time. While the distinction between time perception and time awareness highlights different aspects of temporal experience (Wittmann and Droit-Volet, 2024), we will use the term time perception throughout this paper for simplicity, unless a statement specifically pertains to time awareness.[2]

With respect to the perception of time, we will focus on what can be referred to as 'filled' or 'loaded time' (Grondin, 1993) and 'empty time' (Zakay and Block, 1997): We define loaded time as the timeframe during which task demands are present and require continuous cognitive and motor processing, such as the stimulus presentation and categorization time in the introductory Stroop example. The intervals without such demands that require only minimal processing, such as the timeframe between stimulus categorization and new stimulus presentation in the Stroop example, would then fit our definition of empty time. In general, tasks can often be divided in loaded and empty time. In the context of a typical experimental task, this distinction is straightforwardly reflected in the stimulus presentation time and the inter-stimulus interval. However, in everyday life, even though the distinction might not be so clear-cut, most experiences contain both loaded and empty time. Periods of intense cognitive or physical work are akin to loaded time, while moments of waiting or transition represent empty time.

As the Stroop example illustrates, the perception of how fast or slow loaded time and empty time are passing is a dynamic process. This perception can shrink and expand over the total duration of a task (see Fig. 1 for a conceptual illustration). Simply put, if the duration of each stimulus (loaded time) feels shorter after repeated presentations, then the intervals between these stimuli (empty time) are likely to feel longer. This is because the objective duration of stimulus presentation and the interval between presentations is constant, but the time it takes a person to process the stimuli is dynamic. Research supports the notion that the duration of a repeatedly presented stimulus feels shorter (Eagleman, 2008; Eagleman and Pariyadath, 2009; Tse et al., 2004).

In our proposal, loaded time is associated with high processing demands, while empty time is linked to low processing demands. Consequently, loaded time relates to effort, and empty time to boredom: Intervals with high task load are typically associated with effort (Edwards and McCormick, 2017), whereas those with low stimulation are often characterized as boring (Martarelli et al., 2024; Meteier et al., 2025; Witowska et al., 2020). Thus, the distinction between empty and loaded time provides a psychologically grounded way to capture differences, as well as the underlying non-static nature of how task characteristics shape how time is perceived. This dynamic of shrinking and expanding loaded and empty time raises the question of how time perception is understood to function in general.

Time perception is generally understood through the lens of pacemaker-accumulator models which offer a cognitive framework for how time perception might function in general. To understand why the subjective duration of events changes with repetition, we refer to Eagleman and Pariyadath (2009). They describe time perception of individual stimuli in terms of the neural effort required to process them and focus on the timing mechanisms of 'automatic' sensations in the sub-second range. By contrast, as many things in everyday life whose duration we judge are in the supra-second range, we will also refer to Wittmann's (2022) embodied time account. The embodied time account conceptualizes time perception via the integration of interoceptive

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[2] Interestingly, under certain conditions people might slightly overestimate the amount of time something took (time perception) but report that time was passing very slowly (time awareness). So, while they are often correlated, the mapping between both concepts is not one-to-one (Martarelli et al., 2024).

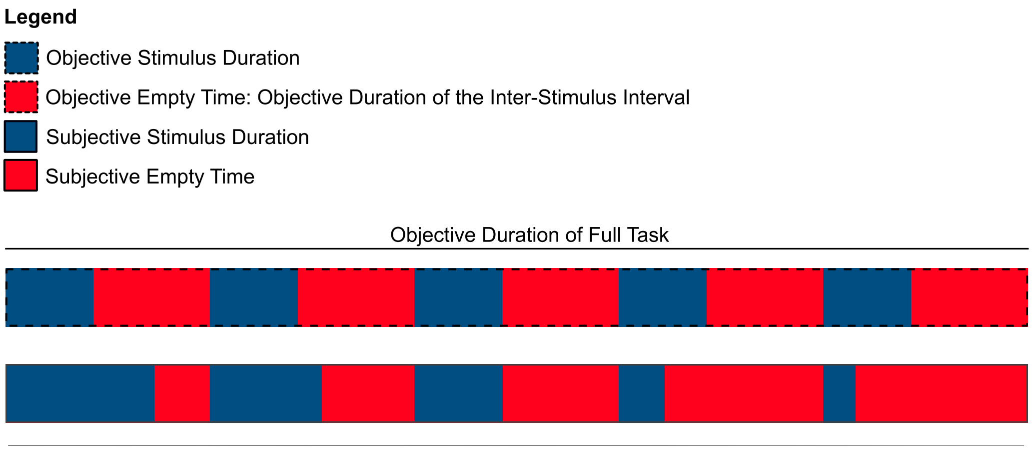

Fig. 1. Schematic visualization of how the duration of the same sensory input, and the space between successive inputs, can feel different when the input is presented repeatedly. More specifically, repeated exposure increases processing efficiency of the presented stimuli, thereby causing loaded time to shrink. At the same time, the subjective experience of the interval between successive stimuli expands, thereby causing empty time to expand. These depicted dynamics relate to the processing demands of the same sensory input over time and the resulting shift in the empty time–loaded time relationship. Importantly, this depiction is agnostic of a potential change in attentional demands during the sequence of events. For example, attentional demands might increase, and performance deteriorate when empty time grows, as boredom sets in, and the person resists the impulse to engage in another activity. However, while not directly within the scope of the present paper, such attention and performance effects would be consistent with the present proposal, as increased processing efficiency is not necessarily linked to improved performance (Ratcliff et al., 2016). In addition, with respect to the changing of loaded time, the depiction does not consider effects, such as the accumulation of fatigue but focuses exclusively on the processing demands of a stimulus/target. If a person were to become fatigued (i.e., processing capacity is reduced), then the same processing demands would require relatively more effort for them, causing loaded time to once more, increase. This implies that the actual dynamics of perceived loaded time would depend on the ratio of how fast processing efficiency increases in relation to how fast fatigue accumulates.

signals processed in the insula, combining affective and cognitive processes. As our proposal is focused on how effort and boredom, as cognitive-affective phenomena, relate to time perception, we will restrict our review of the neuroscience of time perception on this body of literature. We will demonstrate that all three perspectives support the idea that effort and boredom can alter time perception.

1.1. Pacemaker-accumulator models of time: boredom and effort increase the accumulator's count rate

The pacemaker-accumulator models of time perception (Treisman, 1963; Wittmann, 2013; Zakay and Block, 1997), suggest that a pacemaker emits regular pulses that are then counted by an accumulator. Crucially, the accumulator is thought to only track these pulses when one is actively attending to time (Wittmann, 2013). A prototypical illustration of this is a person sitting in a waiting room, bored. With no distractions, the person's attention is drawn to the passage of time, allowing the accumulator to count more pulses. As a result, time may feel like it is dragging on, leading the person to overestimate how long they have been waiting. Indeed, a number of waiting room studies have found support for the claim that time drags on when waiting (Martarelli et al., 2024; Witowska et al., 2020). Supporting boredom's role in this, we found a strong positive correlation between boredom and the perceived slowing of time in a recent waiting room study (Martarelli et al., 2024). Interestingly, the correlation was substantially larger if participants explicitly referred to time awareness and not more generally to time perception. That is, boredom was strongly linked to how slow the passing of time felt, but less so to the estimation of *how much* time had elapsed. Further, a recent study found that participants who had to silently spend time in a boring environment, such as a seminar room, were more aware of time and felt it passed more slowly compared to when they spent time in a less boring environment, like nature (Pfeifer et al., 2023). This finding is consistent with the idea that being bored while waiting increases one's awareness of time, causing the pacemaker to track more pulses in a given timeframe.

Importantly, this example does not only hold for empty time like sitting in a waiting room but also for loaded time in a high effort scenario. For example, during a cycling ergometer task that gets progressively harder over time, an athlete's attentional focus might be primarily concerned with the seconds ticking down until they can finally stop the exhausting task. Again, time will feel like it is dragging, and the athlete is likely to overestimate how long they actually cycled. Supporting effort's role in time perception, research from sport science has shown that during very hard physical efforts people estimate that more time has passed than actually has (Edwards and McCormick, 2017; Hanson and Lee, 2020). With respect to cognitive effort, research shows that people overestimate how long a task took when it had required cognitive effort (Block et al., 2010).[3]

This implies that empty time and highly loaded time can feel long because attention is either explicitly directed toward the passage of time or because bodily states produce a high number of pulses that can be tracked. Indeed, pacemaker-accumulator models further posit that the pacemakers' pulse frequency increases as a function of arousal (Wittmann, 2022). Thus, in high arousal states, such as the ergometer ride, more pulses should be emitted and tracked by the accumulator, again creating the feeling that more time has passed. A similar mechanism may explain boredom, although the relationship between boredom and arousal is more complex. Research suggests that boredom can occur in both high- and low-arousal states, which could lead to differing outcomes for pulses emitted by a pacemaker. However, arousal may not be the sole aspect influencing the perception of time - it may be sufficient that attention is directed toward time, increasing the pulses counted by the accumulator.

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[3] Although people seem to treat cognitive and physical effort differently (Wolff, Stähler, et al., 2024), similar theoretical frameworks have been used to explain the processes by which effort signals are integrated and processed by the brain (Wolff et al., 2021). In turn our proposal is not specific to either form of effort.

1.2. How boredom and effort affect the functional processing of time

In this perspective, we have suggested that effort and boredom shape our experience of time. This should increase the number of pulses that are tracked in a given timeframe, which is expected to lead to an expansion of loaded (in high effort) and empty time (boredom) alike. However, although pacemaker-accumulator models offer a useful framework to describe the perception of time, a specific modality that represents a physical counterpart to the metaphorical pacemaker and accumulator has not yet been identified. Here, we turn to two promising accounts that attempt to explain the functional processing of time and whose propositions are consistent with our proposal that effort and boredom affect time perception across different temporal ranges.

Focusing on events in the millisecond range, Eagleman and Pariyadath, propose that subjective duration is determined by the amount of effort it took to process a stimulus (Eagleman and Pariyadath, 2009). This neural energy hypothesis is consistent with our introductory Stroop example, though it should be noted that Stroop responses unfold on a somewhat longer timescale than the millisecond-range: The same stimulus starts to feel progressively shorter when it is presented repeatedly (Pariyadath and Eagleman, 2007) with subjective shortening accompanied by diminished cortical firing rates in response to repeated stimulus presentation (Grill-Spector et al., 2006). More generally, this implies that after repeated or prolonged presentation of any stimulus, the environment becomes more predictable, processing becomes more efficient and therefore less effortful, which in turn makes the stimulus feel shorter. The proposed increase in processing efficiency is consistent with research on habituation, finding reduced sensory, neuronal, and behavioral responsiveness when stimuli are repeatedly presented (Klingner et al., 2011; Rankin et al., 2009; Thompson and Spencer, 1966). This model offers a mechanistic explanation for why we experience a shift in perceived stimulus duration over time: If a stimulus is processed more efficiently and therefore feels shorter, this should shrink the loaded time and increase the empty time between successive stimulus presentations (for a tentative explanation of how these changes to time perception on the stimulus level could translate to changes in overall time perception of experimental blocks or activities that consist of separate stimuli, see Box 1).

While the neural energy hypothesis (Eagleman and Pariyadath, 2009; Pariyadath and Eagleman, 2007) offers an explanation for why high effort situations are likely to be perceived to last longer, how does this relate to boredom? The expansion of empty time is prototypical for boredom (incidentally, the German word for boredom - Langeweile - literally translates to ‘long while’). As most readers can attest, when we are repeatedly exposed to the same input, we tend to become bored (Berlyne, 1960; Gomez-Ramirez and Costa, 2017). Expressed more technically, it has been suggested that boredom occurs when the environment does not generate sufficient informational value, which would indicate suboptimal learning rates and reward prediction errors that have been minimized because one’s environment has become overly predictable (Darling, 2023; Gomez-Ramirez and Costa, 2017; Wolff, Radtke, et al., 2024). Prototypically this can occur in situations where entropy is low (Seiler et al., 2022). So, as stimuli are processed more efficiently and feel shorter, empty time expands and one experiences less ‘news’ from the environment (i.e., minimized reward prediction error, low entropy). But how might boredom now create the feeling of ‘long while’?

When bored, people increase their motor and mental activity in search for more rewarding things to engage in (Wolff, Radtke, et al., 2024). It has been shown that people find doing nothing aversive (Wu et al., 2023). Consistent with this, an emerging body of research shows that bored people display higher rates of non-instrumental movements (Witchel et al., 2016), for example repeated pressure changes on the chair while sitting (D’Mello, 2007) or off-target gaze behavior (Wolff, Radtke, et al., 2024). This is consistent with research showing that feeling bored is associated with self-reported restlessness (Danckert et al., 2018).[4] In addition to unspecific motor activity that occurs when bored, boredom is also linked to mind-wandering, with the link to spontaneous mind-wandering being particularly strong (Martarelli and Baillifard, 2024). As these findings indicate, boredom appears to increase attention to one’s internal (bodily and mental) states, making one notice their own discomfort or that one’s thoughts are drifting away. Supporting this claim, recent work has shown that people who are frequently bored report greater attention to interoceptive signals (Trudel et al., 2024). While boredom likely increases sensitivity to exteroceptive signals as well, here we focus on its link to interoceptive signals and how this relates to time perception. To do so, we turn to Wittmann’s interoceptive embodied time account to propose an explanation of how boredom and effort can create the feeling that time is passing slowly (Wittmann, 2022).

According to Wittmann, the number of interoceptive signals that an agent attends to indicates how much time has elapsed. Through the lens of pacemaker-accumulator accounts this implies that various interoceptive bodily signals contribute to our perception of time. As no specific sensory organ for tracking time appears to exist in the human body, this embodied account—where multiple interoceptive signals collectively shape the experience of time—provides an elegant explanation for human time perception. This approach is especially compelling because sensory experiences inherently possess a temporal quality. To illustrate, one might feel a moderate degree of discomfort while sitting on a chair (signaled by nociceptor activity) for a certain amount of time.

But how does the embodied time account relate to boredom and boredom’s effect on how we perceive the passage of time? When loaded time shrinks and empty time expands (e.g., as one becomes more proficient at processing environmental inputs; Eagleman and Pariyadath, 2009), boredom is likely to occur. Boredom is associated with increased interoceptive awareness - such that bodily signals are more assiduously attended to - and with a drive to seek additional sensory input, thus generating more interoceptive signals. In addition, boring situations are prototypically characterized by a lack of relevant/rewarding exteroceptive signals (e.g., interesting things to hear, see, or taste), further tilting the balance towards heightened interoceptive awareness. Boredom should therefore impact time perception in two ways: first, because pulses (interoceptive signals) are tracked at a higher rate when one is bored, and second, because additional pulses are generated due to heightened interoceptive awareness.

The embodied time account is also consistent with research showing that high effort activities tend to feel longer than low effort activities (Edwards and McCormick, 2017; Hanson and Lee, 2020): When time is loaded with processing demands, interoceptive signals are generated at a higher rate. For instance, as an exercise session intensifies, an exerciser’s heart will beat more frequently, increasing interoceptive signaling. Likewise, in the first block of a demanding Stroop task, an overwhelmed participant will focus on multiple unfamiliar stimulus features, again allowing for more interoceptive signals to be accumulated by the pacemaker. In both cases, the high processing load should generate more pulses that can be tracked by the pacemaker, creating the feeling that more time has passed than actually has.[5] Notably,

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[4] Interestingly, providing people opportunities to engage in fidgeting behavior to reduce boredom does not appear to be effective (Spencer-Mueller and Fenske, 2024). One reason for this might be boredom motivates the *search* for rewarding things to engage in and provision of outlets for one’s restlessness could potentially defeat this very function of boredom.

[5] Please note, that this might also be described as a speeding up subjective time, as the person estimates to have performed an activity for more seconds than they actually have. So, relative to chronological time, subjective time has sped up. At least one of the authors can attest to the agony of this experience when – during a high intensity cycling effort – one thinks the three minute effort block should be almost finished by now, only to find that one is only halfway through it.

Box 1
– Perceived total subjective duration as the sum of empty and loaded time.

Let's briefly return to our initial example of the dynamic changes of perceived duration during a Stroop task: If loaded time and empty time change as a function of processing efficiency and if time passes very slowly during highly loaded or empty timeframes, this begs the question of how total duration of any given timeframe is affected by these changes. Put simply, since any situation consists of a mix of empty and loaded task demands, how is the overall experience of time shaped by this mix? In our initial example, during the first five minutes, time felt 'loaded' because processing and categorizing word stimuli required high amounts of cognitive effort. In the last five minutes, time felt empty because processing and categorizing the stimuli had become almost second nature to the person. So, in the first example, most of the five minutes consisted of loaded time (almost no empty time) and in the second example the empty time/loaded time ratio was reversed. In both cases time seemed to pass slowly. But what is the computational underpinning of this observation? We suggest that the experienced total time is the sum of time perception during empty time and loaded time. While the exact temporal dynamics of how these periods shift with repeated presentations remain an open question, research in related areas, such as habituation, often points towards exponential changes (Rankin et al., 2009) or sigmoidal changes (Aerdker et al., 2022). If similar dynamics apply to empty and loaded time, we might predict that total subjective duration is longest at the extremes—when feelings of either effort or boredom are at their most intense (Fig. 2). However, further research is needed to test this prediction and to better understand the temporal dynamics underlying these shifts.

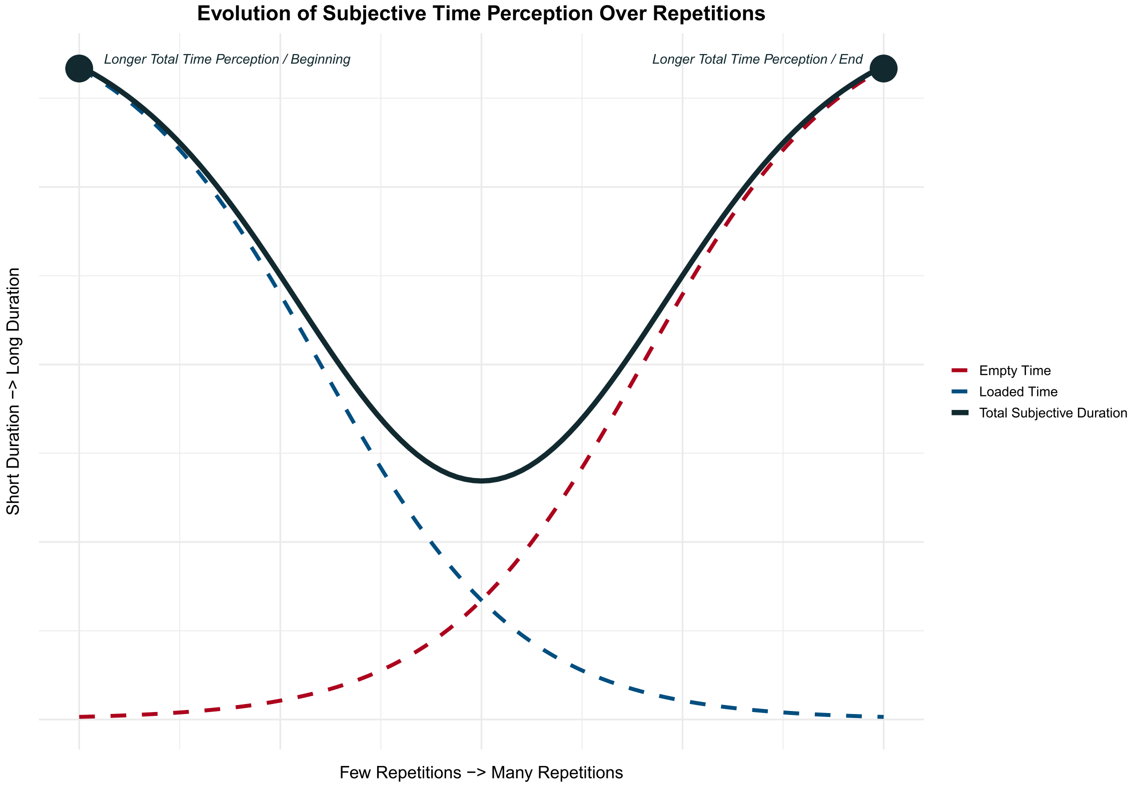

Fig. 2. Conceptual representation of how the total subjective duration of an activity might be affected by the dynamic changes in empty time and loaded time for processing the chunks that make up the activity. More specifically, it visualizes how the perceived total duration of an activity might change as a function of the frequency with which chunks that make up the activity must be processed. At the beginning of an engaging activity, the novelty requires more effort, making time seem to pass more slowly (see loaded time, blue curve). As the task becomes more familiar through repetition, the required effort decreases, and time seems to shorten. However, with further repetition and the onset of boredom, time starts to stretch again (see empty time, red curve). Total subjective duration of an activity or an experimental block (see black curve) combines both the loaded and the empty time. *Note.* The conceptual model visualizes these dynamics as a sigmoidal function for empty time and loaded time. We have chosen this function over an exponential function as this does not force empty time and loaded time be infinitively high at the extremes.

interoceptive sense data have relatively low spatial specificity making their experience more diffuse (compared to vision, for example; Feldman et al., 2024), and an effort-applying person is likely to causally attribute the most notable interoceptive changes to the effort they are exerting. In contrast, the interoceptive changes that are associated with being bored will likely evade such a causal interpretation by the bored person. The relative amorphousness of feeling bored is also reflected in the heterogenous findings linking boredom to low, mixed or even high arousal (Wolff, Radtke, et al., 2024). Irrespective if the experiencing agent causally attributes interoceptive signals to heightened effortful processing demands or experiences them as an unspecific corollary of boredom, both scenarios are expected to change the perception of time in the same direction.

Taken together, the neural energy hypothesis provides a mechanistic explanation for why the same sensory input can feel longer or shorter. It illustrates how situations can shift from high effort to boredom as the neural energy required for processing changes dynamically. Building on this, the embodied time account explains how effort and boredom influence interoceptive signaling and awareness of bodily signals. Thereby offering a functional explanation for why effort and boredom can make time feel as though it is dragging on.

1.3. How the neuroscience of time perception aligns with effort and boredom research

So far, we have discussed how boredom and effort influence the subjective experience of time. First, we have examined this conceptually through the psychological pacemaker-accumulator model of time perception. Second, we have turned to the neural energy hypothesis (Eagleman and Pariyadath, 2009) and the embodied time account (Droit-Volet et al., 2020; Wittmann, 2022) to highlight putative mechanisms through which boredom and effort affect the functional processing of time. Building on this, we will now review neuroscientific research on insula activity that might offer insights into the mechanistic underpinnings of the link between boredom, effort and time perception.

The insula has been identified as a key structure for processing bodily, affective, and cognitive states, and it plays a regulatory role in decision-making by integrating interoceptive and exteroceptive information (Zhang et al., 2024). While the insula is recognized as a hub that integrates both interoceptive and exteroceptive information (Allen, 2020; Simmons et al., 2013), we propose that in the specific contexts of boredom and effort, interoceptive signals may become disproportionately influential. When external stimulation is reduced (as in boredom) or when internal bodily load is heightened (as in effort), attention may shift inward, making interoceptive cues the dominant substrate for temporal experience. More specifically, and relevant for this perspective, the insula has been implicated in interoception (Craig, 2009; Namboodiri and Stuber, 2020; Saper, 2002; Vicario et al., 2020), time perception (Teghil, 2024; Vicario et al., 2020; Wittmann and Droit-Volet, 2024), boredom (Dal Mas and Wittmann, 2017; Danckert and Merrifield, 2018; Drody et al., 2024), and effort (Hogan et al., 2020; Müller and Apps, 2019; Zhang et al., 2024). Recent meta-analyses using the activation likelihood estimation technique further suggest that the insula is one of the central hubs in time perception across timescales (Mondok & Wiener, 2023), from sub-second events to extended durations (Naghibi et al., 2024). Notably, Craig (2009) had already theorized that the insula constitutes a decisive brain region for understanding subjective time. Anatomically, the human insula consists of various subregions that differ in lamination and cytoarchitecture (Feldman et al., 2024; Uddin et al., 2017; H. Zhao et al., 2023). In the context of this paper, we will only broadly differentiate between functions along the posterior-anterior axis. The processing from high-dimensional representation into more low-dimensional multimodally integrated representations appears to progress along a dorsal-posterior to ventral-anterior gradient (Feldman et al., 2024). Posterior parts of the insula seem to be the key structure for receiving and integrating various interoceptive signals. These are then passed on to the anterior insula to be processed for higher order representations (Craig, 2009; H. Zhao et al., 2023). Simply speaking, posterior parts of the insula appear to be more relevant for processing raw signals, whereas anterior parts seem to be more involved for processing these into more abstract cognitive-affective signals/states.

The accumulation of interoceptive signals as a meter of elapsed time has been associated with activity in the posterior insula (Wittmann et al., 2010). A neural mechanism called *climbing neural activation* where neural activity gradually increases or decreases during a timed interval, peaking at its end, has been proposed to underly the tracking of time in the posterior insula (Wittmann, 2013). Consistent with the dorsal-posterior to ventral-anterior gradient of increasing complexity, anterior insula activity has been associated with reproduction of time intervals (Wittmann et al., 2010) or the accuracy of duration discrimination (Hashiguchi et al., 2022). These findings are consistent with the view that time perception is embodied and influenced by internal bodily states (Droit-Volet et al., 2020; Wittmann and Droit-Volet, 2024). In turn, feelings that can affect the magnitude of and sensitivity to such bodily states, such as boredom and effort, could be expected to dynamically affect time awareness through their effect on insula activity.

So far, only few studies have investigated the neuroscience of boredom (for an overview, please see Drody et al., 2024) with the anterior insula regularly implicated in research that has investigated the bored brain. Being bored has been linked to reduced activity in the anterior insula (Danckert and Merrifield, 2018). However, when people tried to reduce their boredom, increases in anterior insula activity was reported (Dal Mas and Wittmann, 2017). Similarly, another study observed less activity in the anterior insula during boredom (when compared to states of flow or overload), but relatively stronger functional connectivity between anterior insula and the ventral striatum (Ulrich et al., 2022). One can speculate that boring situations characterized by an initial lack of relevant things to engage in, are then met by attempts to address this state by increasing the number of things the person tries to attend to or engage with. The former state is then expected to be characterized by reduced anterior insula activity, whereas the latter would correlate with increased anterior insula activity and/or heightened connectivity with regions that allow for the exploration of viable things to engage in. To the best of our knowledge, boredom has not been linked to altered activity in the posterior insula. A speculative interpretation is that boredom's effect on time perception may stem less from increasing the number of pulses accumulated by the pacemaker and more from directing attention to these pulses in the absence of relevant exteroceptive information. During periods of empty time, the anterior insula may become more sensitive to internal bodily states, as boredom is associated with increased interoceptive sensitivity (Trudel et al., 2024). Since time perception is influenced by how much attention is paid to its passage, boredom may make available more attention to focus on internal sensations, such as heart rate, breathing, and posture. This hyperawareness of bodily states may amplify the feeling that time is moving slowly. In states of boredom, when prediction errors are low (i.e., there are no unexpected events or new stimuli) the anterior insula becomes more focused on internal states, further enhancing time awareness. Conversely, when prediction errors are high (due to surprises or rewards), external stimuli capture attention, reducing boredom and making time seem to pass more quickly. Indirect evidence for a link between attentional focus and time perception comes from research showing that situational increases in interoceptive awareness led participants to overestimate time, whereas situational increases in exteroceptive attention led participants to underestimate time (Richter and Ibáñez, 2021).

The posterior and anterior insula have also been associated with effort in neuroscientific research (Müller and Apps, 2019; Williamson et al., 1999). Consistent with its function as a key hub for interoception, posterior insula activity has been related to sensations such as pain (Horing and Büchel, 2022) or tachycardia (Chouchou et al., 2019), and the sensing of aversive states in general (Gehrlach et al., 2019), all of which contribute to feelings of effort. Further, effort demanding tasks are related to increased activity in anterior and posterior insula and activity profiles in the posterior insula have been linked to feelings of fatigue, a consequence of prolonged effort exertion (Meyniel et al., 2013; Müller and Apps, 2019). Again, in keeping with the dorsal-posterior to ventral-anterior gradient, anterior insula activity has been found to play a role in decisions to invest or withhold effort (Arulpragasam et al., 2018; Chong et al., 2017) or feelings of fatigue as a more generalized cumulative consequence of exerting effort (Müller and Apps, 2019). The evidence linking effort and insula activity aligns with the idea that effort demanding situations alter the number and the intensity of interoceptive signals that are processed by the insula, thereby potentially directly affecting how we perceive the passage of time.

Beyond its role in interoceptive processing, the insula is a central hub for predictive coding (Corlett et al., 2022; Ficco et al., 2021). Specifically, the anterior insula appears to be involved in the integration of interoceptive signals with prediction error signals, thereby allowing mismatches between experienced and expected bodily states to be tracked (Gu et al., 2013). The role of the insula in predictive coding points towards a complementary insula-mediated process that explains how boredom and effort shape the experience of time. Boredom has been defined as a state where predictive error signals are minimized because things become too predictable (Wolff, Radtke, et al., 2024), biasing processing towards an increased awareness for interoceptive signals. In contrast, prediction errors increase when an action was more effortful than expected (Tanaka et al., 2021), thereby potentially amplifying the interoceptive signals that are tracked by the anterior insula. Thus, the degree to which an expectation-experience mismatch occurs might cause re-weighing of interoceptive signals and changes in perceived duration. These two processes also align with the dorsal-posterior to ventral-anterior gradient, where in the posterior insula appears to be primarily involved in processing raw bodily input, while the anterior insula integrates this with predictive models (Craig, 2009; H. Zhao et al., 2023). From this perspective, distortions of temporal experience in boredom and effort reflect not only the salience of interoceptive signals, but also the predictive context in which they are processed.

Taken together, effort and boredom have been conceptually and empirically associated with heightened interoceptive signaling or interoceptive awareness, and insula activity has been observed to increase in response to a wide range of interoceptive signals (Craig, 2009), which may account for its engagement during both effort and boredom. The extant neuroscientific evidence is therefore largely consistent with the proposal we have outlined in this paper. Namely, that boredom and effort increase awareness to internal bodily states, thereby altering the number of pulses the ‘internal clock’ tracks.

1.4. *Open questions and further research*

We have written this perspective through the lens that effort and boredom alter the perception of time because effort and boredom inductions change how time is perceived (Behm and Carter, 2020; Martarelli et al., 2024). This presumed directionality invites a set of promising research questions to fully test the assumed causal links and the generalizability of these to different time scales. For instance, one might also make the case that the relationship between effort, boredom and time perception we outline here operates in the reverse. Existing evidence remains largely correlational, and causal dynamics between these processes remain speculative. For example, recent work has shown that individual differences in interoceptive awareness predict changes in subjective time more strongly than self-reported boredom (Droit-Volet et al., 2025), supporting the idea that bodily awareness plays a central role in temporal experience. Future research could therefore test directionality by manipulating levels of effort or boredom while tracking changes in interoceptive processing and temporal judgements. Another promising line of research would be to manipulate interoceptive versus exteroceptive focus through physiological perturbations (e.g., heartrate feedback, controlled breathing) or by applying non-invasive neuromodulation to the insula. Experimental paradigms with high temporal resolution that integrate psychological, neural, and physiological measures would be particularly valuable to map the dynamics of effort, boredom, and time perception in real time. Furthermore, individual differences in boredom tolerance (Bieleke et al., 2022) or the subjective valuation of effort (Wolff, Stähler, et al., 2024) may explain variability in how these states influence temporal judgments and should be considered in experimental designs. Taken together, such approaches would allow us to clarify whether effort and boredom drive temporal distortions via interoceptive mechanisms, whether altered time perception itself feeds back into the experience of effort and boredom, and more broadly, whether internal and external signals make distinct contributions to subjective time.

Another avenue for future research lies in testing how effort and boredom shape the perception of time across different temporal ranges. This is particularly important because the neural energy hypothesis focuses on very short time frames (sub-second) and the embodied time account on relatively longer timescales. We have suggested that the experienced total time is the sum of time perception during empty time and loaded time, implying that those time windows require dynamically varying degrees of to-be-processed information (see Box 1). Extending this logic, longer time windows may be conceptualized as comprising multiple to-be-processed stimuli which, in addition to being captured by the neural efficiency hypothesis alone, combine into an embodied perception of overall event duration. Supporting this view, meta-analytic evidence indicates consistent insula involvement across different temporal ranges (Naghibi et al., 2024). At the same time, it is likely that the broader neural circuitry for processing different timescales differs, as longer durations likely involve a higher degree of mnemonic processes and anticipatory mechanisms. For our proposal this is a particularly relevant research question given that expectations and post-hoc evaluations of effort and boredom could shape how an action is approached, perceived and evaluated (Cheval et al., 2025). Future research could also test whether these processes differentially influence primary (online) duration judgments, made in real time, versus secondary (retrospective) judgments, formed after an event has ended.

Finally, our perspective has potential implications for real-world task performance. Understanding how momentary boredom and effort dynamically shape time perception can inform how people interact with tasks. For example, prompting them to rush when bored to avoid wasting time, or indicating when task demands might need to be adjusted to match an individual’s current capacity. This highlights that temporal experience is not static: the same task can feel long or short depending on transient fluctuations in effort and boredom, suggesting opportunities for adaptive task design.

2. Conclusion

In this perspective, we propose a tentative explanation for why events of the same objective duration can feel as if they pass faster or slower, focusing on the roles of effort and boredom in shaping time awareness. We suggest that increasing exposure to a task improves the efficiency of processing external and internal sensations, thereby altering how ‘empty’ or ‘loaded’ a timeframe feels. While effortful situations are characterized by a higher share of loaded time, boredom is characterized by more empty time. Importantly, both sensations contribute to the feeling that time is dragging. Mechanistically, boredom and effort might influence time perception by increasing attention to internal bodily states. In line with this argument, both effort and boredom have been linked to heightened interoceptive signaling and sensitivity, processes that appear central to time perception through the integration of interoceptive signals. At the neural level, the insular cortex emerges as a promising candidate region for understanding this relationship, as it serves as a key hub for boredom, effort, interoception, and time perception.

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During the preparation of this work the author(s) used ChatGPT in order to remove typos and improve readability of some sentences. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

No data was used for the research described in the article.

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