Trends in Cognitive Sciences

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Opinion

The computational structure of consummatory anhedonia

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Anhedonia is a reduction in enjoyment, motivation, or interest. It is common across mental health disorders and a harbinger of poor treatment outcomes. The enjoyment aspect, termed 'consummatory anhedonia', in particular poses fundamental questions about how the brain constructs rewards: what processes determine how intensely a reward is experienced? Here, we outline limitations of existing computational conceptualisations of consummatory anhedonia. We then suggest a richer reinforcement learning (RL) account of consummatory anhedonia with a reconceptualisation of subjective hedonic experience in terms of goal progress. This accounts qualitatively for the impact of stress, dysfunctional cognitions, and maladaptive beliefs on hedonic experience. The model also offers new views on the treatments for anhedonia.

Highlights

Traditional reinforcement learning (RL) accounts of consummatory anhedonia suggest that a blunting of the reward function underlies reduced hedonic experience.

However, these existing RL methods cannot provide a mechanistic explanation of consummatory anhedonia, related aspects of depression, or potential treatments.

We outline a new model that builds on theories of physiological drive to reconceptualise subjective hedonic experience in terms of progress towards individually meaningful goals.

Using an RL framework, we can consider how stressful events, attribution of negative meaning, and persistence with unachievable goals may alter perceived goal progress and subsequently lead to anhedonia.

Anhedonia

How much less would you enjoy your favourite meal after losing your job, and how much more after a promotion? Hedonic reactions to individual events are all but fixed and derive their colour and richness from the context of our lives. For individuals suffering from **anhedonia** (see Glossary), who report a lack of pleasure in most activities, a negative context adds dark colours to all experiences.

Anhedonia is a persistent loss of interest in or pleasure from previously rewarding activities [1]. From a clinical perspective, understanding anhedonia is important: it is a common feature of many mental illnesses [2–4], particularly depression [1]. Its presence is associated with poorer outcomes, including longer depressive episodes [5,6], increased risk of suicidal ideations and suicide attempts [7–9]and reduced responsiveness to psychological [10] and pharmacological [11] treatments.

However, anhedonia is a complex construct, with different definitions and conceptualisations reflecting a range of clinical, social, and cognitive factors [12] stretching across computationally and neurobiologically distinct processes [3,13]. One key and computationally relevant distinction is between the diminished pleasure experienced during events, '**consummatory anhedonia**', and the more anticipatory components, such as the diminished interest in the events from afar, or the motivation to pursue the rewards, termed '**motivational anhedonia**' [14,15]. These are thought to reflect the preclinical concepts of 'liking' and 'wanting', respectively, and thereby link to neurobiological substrates [16,17]. While the motivational aspect has been seen as a reflection of components of (possibly dopaminergic) model-free [13,18–20] **reinforcement learning (RL)**, the process of liking and consummatory anhedonia remains less clear [17]. Consummatory anhedonia itself poses an interesting theoretical puzzle: it is typically conceptualised as affecting individuals' capacity to experience rewards, but a fundamental alteration to an organism's **reward function** is a drastic change with vast organismal consequences.

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It therefore poses the complex question of how the brain solves this control problem: what should the brain find rewarding and why?

Here, we extend the RL account to consummatory anhedonia, arguing that RL provides a coherent framework within which to conceptualise and understand subjective experiences of reward in anhedonia [21]. We consider how to capture effects of meaning and interpretation within a model-based (or theory-based [22]) RL framework. We start by reviewing existing results on RL and anhedonia and identify their main conceptual shortcomings. Building on theories of physiological drive and appraisal, we reconceptualise **subjective hedonic experience** in terms of **goal** achievement within a **belief structure**. Challenging traditional assumptions, we propose that human 'liking', or hedonic experience, includes a fundamentally motivational aspect akin to a high-level model-based 'wanting' [17]. We describe it as an inferred quantity [23,24] sensitive to internal beliefs, fundamentally related to inferred progress towards individually meaningful goals or 'personal values' [25]. The core argument is that events or outcomes that increase the perceived distance to such goals or values reduce hedonic experience by reducing perceived progress of self-fulfillment, and RL mechanisms provide the machinery to evaluate this progress. We outline how this framework can qualitatively capture numerous aspects of anhedonia and outline its implications for the treatment of anhedonia.

Standard RL accounts suggest consummatory anhedonia is a reduction in reward sensitivity

RL concerns the problem of identifying optimal behaviours, that is, behaviours with maximal long-term returns, when the informative teaching signal is delayed [26]. A typical example is chess, where it can be difficult to know how much each particular move contributed to a win or loss. For our purposes, the key ingredients of RL problems are a reward function $\mathcal{R}$, a value function $\mathcal{V}$, prediction errors δ, and value changes $\delta\mathcal{V}$ (Box 1).

One core computational suggestion has been that consummatory anhedonia reflects a blunting of the reward function $\mathcal{R}$ [19,27–29], possibly due to opioid system alterations [30]. Indeed, consummatory anhedonia is often accompanied by indifference to designated, often monetary, 'rewards', with participants with anhedonia showing a reduction in the development of a behavioural bias towards the more rewarded of two choice options [19,31–37]. A computationally related suggestion is that of increased sensitivity to losses [38–40], particularly effort costs [3,41] possibly due to inflammatory [20] or dopaminergic changes [42]. An alteration of $\mathcal{R}$, be it a blunting of the positive, reward side, or an increase in the negative, loss side, is in principle a powerful explanatory device, as it can in principle explain vast changes, including changes in motivation, vigour, and psychomotor speed.

However, this computationally simple account fails on several fronts [13,21]. First, diminished subjective reward experience suggests individuals with consummatory anhedonia should have a generalised reduced hedonic response to the sensory experience of rewarding events. This would predict that such individuals should provide a lower rating of the hedonic value of all primary rewards, in the absence of learning. This question has been addressed in a number of studies, consistently finding that symptoms of depression and anhedonia are associated with a decreased ability to discriminate between different sensory stimuli [43–46], but there has been no consistent finding that the hedonic value of the stimuli are attenuated [43,44,47–50]. Second, the attenuation of hedonic response is more visible in more complex stimuli [51], including visual, social, and epistemic stimuli [52], which do not have any obvious primary 'reward' value. Third, there has been ambiguous neuroimaging support for a neural reduction in reward sensitivity. The most common finding is a reduced response to the anticipation of reward rather than the consumption of reward [53–59], but these have not been uniformly seen ([60–62]; see also

Glossary

Anhedonia: persistent loss of interest or pleasure in previously rewarding activities.
Belief structure: an internal representation of the environment that encapsulates how behaviours move the individual between conceptual states in the environment.
Consummatory anhedonia: persistent diminished hedonic experience in response to reward.
Goal: a state that influences behaviour with the aim of achieving said state.
Motivational anhedonia: diminished motivation to pursue reward.
Reinforcement learning (RL): learning what actions to take in an environment so as to maximise reward.
Reward function: a function assigning a scalar reward (if positive) or punishment (if negative) to each state and action.
Set-point: the point where all drives are satisfied, or at which all current goals are reached.
Subjective hedonic experience: the subjective experience of pleasure or enjoyment.
Value $\mathcal{V}^{\pi}(s)$ of the state: long-term expected reward when starting in a state.

Box 1. Reinforcement learning (RL) and the reward function

RL concerns situations where informative feedback is both sparse and delayed [26]. This results in challenging credit assignment problems. RL formalises this as Markov decision processes, where taking a particular action a in a state s results in a transition to some new state s' with a probability $\mathcal{T}(s|',sa)$ and reward $\mathcal{R}(s,',sa)$ that depends on the current state s, the action a, and the next state s'. $\mathcal{T}$ and $\mathcal{R}$ together define a 'model' of the world, because they express a person's belief about what effects actions have and what is good or bad.

The aim of RL is to identify an optimal policy $\pi(a|s)$ that defines which actions a should be taken in each state s. The optimal policy is defined as earning the maximal total sum of rewards from now until some distant future. The expected sum of total rewards when starting in a state s and behaving in a particular way (following a particular policy π) is the **value $V^{\pi}(s)$ of the state s**. This value can be written as

$$\mathcal{V}^{\pi}(s) = \langle \mathcal{R}(s',a,s) \rangle + \langle \mathcal{V}^{\pi}(s') \rangle \quad [\mathrm{I}]$$

where the first term on the right is the reward received at that state and the second term the value of the subsequent state, both averaged over how likely each of these are given the current policy.

For the current purposes, two aspects of this value function are important. First, Equation I relates the reward at any distant state s' to the current state s. For instance, although there is only a reward in the centre of the environment (Figure IA), the value function has informative structure. In Figure IB, for a random walk, it increases with proximity to the reward. In Figure IC, for a random walk biased to the right, states to the left have higher value. Hence, states can have value even if they do not immediately result in reward, simply because they indicate a possible future reward.

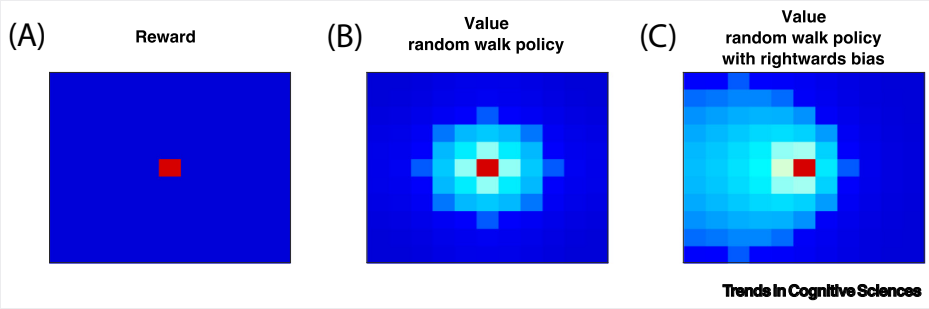

Figure I. Reward and value. (A) In situations with only a single reward in an environment, represented here by the red square, the reward function provides little information as the rest of the environment, represented in blue, has a flat signal. However, the value function has a more informative structure, whether the policy is a random walk (B) or biased (C). Here, the value increases with proximity to the reward, with lighter blue representing higher value.

Second, if the assumptions an individual made about future rewards are wrong, then the right and the left side of Equation I will not match, resulting in a prediction error upon moving from one state to another:

$$\delta = \mathcal{R}(s',a,s) + \mathcal{V}^{\pi}(s') - \mathcal{V}^{\pi}(s) \quad [\mathrm{II}]$$

Furthermore, in states where no immediate reward is obtained $\mathcal{R}(s,',as) = 0$, the prediction error reduces to the change of the value function:

$$\delta\mathcal{V} = \mathcal{V}^{\pi}(s') - \mathcal{V}^{\pi}(s) \quad [\mathrm{III}]$$

A positive value change in the absence of an immediate reward indicates that the organism makes (unexpected) progress towards a reward and reduces the behavioural distance to the reward. Critically, $\delta\mathcal{V}$ will tend to be shallower further away from the reward as the value function flattens out in the distance.

[63]). Finally, and maybe most importantly, the characterisation of anhedonia as a global blunting of $\mathcal{R}$ is not a mechanistic explanation as it does not explain the origin or aetiology of this alteration. It does not explain why anhedonia is related to a loss of purpose or meaning [64], or how and why treatments work. Furthermore, it raises more questions, including what hedonic experience is and how it is controlled in the absence of anhedonia.

We note here that a number of studies have reported an association between anhedonia and a reduced learning rate (e.g., [33,65,66]). These changes likely speak more to the motivational components of anhedonia, the reductions in 'wanting' observed behaviourally, than the reductions in hedonic experience.

Ingredients of a richer RL model of anhedonia

We now outline a simple novel computational account of consummatory anhedonia. The aim is to address the shortcomings outlined earlier and to provide a mechanistic account of several additional phenomena: the relationship between anhedonia and stress; meaning, appraisals, and goal-persistence; and treatment considerations.

From rewards to goals and value change

The reward sensitivity account of consummatory anhedonia ultimately implies some alteration to the underlying primary evolutionarily-defined reward function $\mathcal{R}$. This links primary rewards directly and tightly to subjective hedonic experience. However, while a relationship between hedonic experience and primary rewards clearly is necessary, the relationship likely does not need to be so tight. Returning to your favourite food, although this has energetic value and as such has some primary rewarding effect, the hedonic experience is far more complex. It reflects idiosyncratic associations and is influenced by apparently irrelevant factors, such as a recent job promotion or rejection.

Two broad sets of findings relating to goals and errors suggest a computational substrate for hedonic experience. First, experiments in which individuals are repeatedly asked to report their momentary happiness have shown that prediction errors have a large impact on subjective emotional states [67–69]. This suggests that hedonic experience is related to changes or differences in values (δ or $\delta\mathcal{V}$ in Box 1). Second, subjectively experienced rewards are highly sensitive to goals. How congruent an outcome is with a goal has a motivating effect on behaviour beyond objective reward [70]; providing goals alters the overall hedonic impact of effortful decisions [71]; and the desirability of objects is continuously updated based on how relevant an object is in achieving currently held goals, with neural remapping occurring in line with these value representations [72]. Indeed, subjective value judgements do not purely reflect objective rewards but also have a functional aspect, depending on the relevance of events to currently held goals [73]. There is evidence that motivation increases with goal proximity and that this is observed because the goal's value function is steeper when goals are more proximal ([74,75]; c.f. Box 1). Goal achievement has also been explicitly considered as the source of an intrinsic reward function [76]. These findings strongly suggest that progress towards goals are important components of subjective hedonic experience.

Managing multiple homeostatic necessities

We build upon RL theories of homeostatic drive reduction (homeostatic RL) which have previously considered the relationship between goal distance and reward [77]. A critical component introduced by homeostatic RL theories is the notion of different dimensions representing different physiological drives, such as the glucose level or internal temperature, with a **set-point** within the space at which drives in all dimensions are satisfied (Figure 1A–C, Key figure). Events (e.g., sunshine) alter the distance to the set-point along one dimension (e.g., temperature) and reward is here defined as the change in distance from the set-point induced by the event. Critically, this engenders sensitivity to how satisfied other drives and other dimensions are. Consider the same event starting either at the top (orange) or the bottom (blue) circle and moving the organism horizontally (Figure 1B). The distance travelled is the same, yet the starting location alters the reduction in distance to the homeostatic set-point. As a result, the reward is greater for

Key figure

A new model of subjective hedonic experience

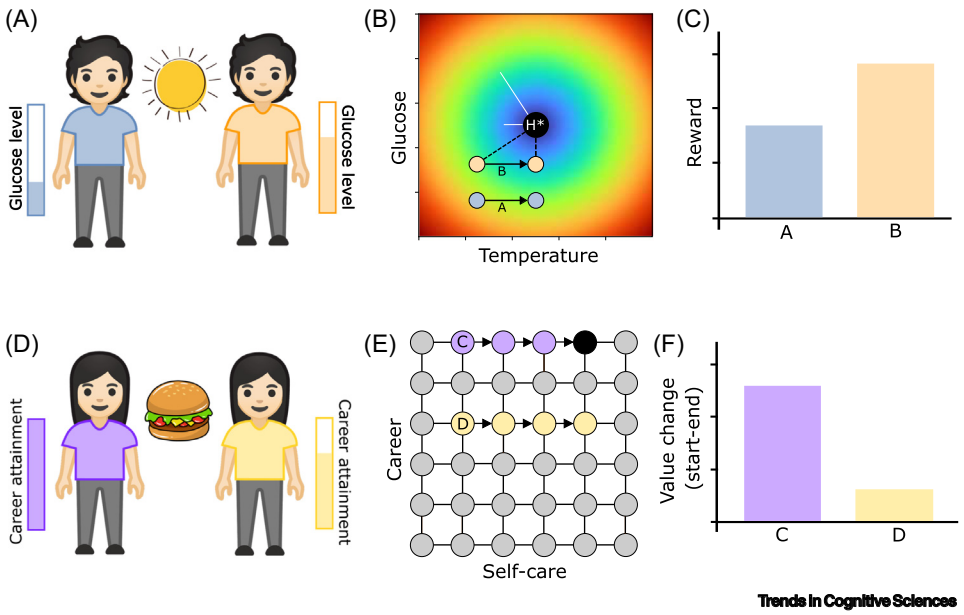

Figure 1. (A) Illustrates a homeostatic reinforcement learning (RL) setting with two individuals who experience different rewards from sunshine due to their unrelated glucose levels. As illustrated in (B), both individuals have a central set-point (H*) where temperature and glucose levels are optimal. Both individuals experience the same increase in temperature from the sunshine, illustrated by the arrows. However, they begin with different glucose levels, with blue having glucose levels at greater Euclidian distance (D) to the set-point than orange, hence at different starting positions (H_0) and end positions (H_1). The reward blue experiences from the sunshine, defined as the change in distance from the set-point $r = D(H_0) - D(H_1)$, is therefore smaller than the reward orange experiences, as illustrated in (C). (D) Illustrates another individual and their hedonic experience on a grid of conceptually defined states akin to the homeostatic situation in (A). In (E), the goal 'set-point' is represented by the black circle and the axes represent the more abstract goals of self-care (i.e., treating yourself to your favourite food) and career attainment (i.e., publishing a manuscript). To achieve the goal of self-care, the agent progresses horizontally to reach the penultimate state from the right. To achieve the career goal, the agent progresses vertically to the top. Together, these dimensions give rise to a multidimensional space where the black state represents goal achievement in both dimensions. The value of states along the purple and yellow paths increases as the agent moves along the self-care dimension towards the goal state, but most rapidly for the purple path, resulting in a larger value change δ. This value change, hence hedonic experience, is illustrated in (F). Very generally, δ will be smaller with increasing distance from the goal.

the orange points than for the blue points: the reward is reduced when the irrelevant dimension (i.e., glucose level) is less satisfied.

Meaning and the value of progress towards goals

Like set points, goals represent states of high incentive salience [74,78,79] that motivate targeted behaviours which ultimately aim to achieve or satisfy the goal [80]. A PhD student may patiently rewrite a manuscript until they reach the state of having published an article on RL theories of anhedonia. Unlike in the homeostatic example, however, the notion of distance to, and hence progress towards, such abstract goals is complex. The publication is not a simple linear function of word count matching the target word count; and different individuals may judge the progress towards a goal very differently depending on their belief structure,

interpretation, and identity. Hence, the simple Euclidian geometry used for the homeostatic RL example will not do in general.

Instead, consider goals in a conceptual or abstract semantic space [81] where states are discrete, high-level complex and conceptually defined objects meaningfully related to internal conceptualisations of the situation at hand. For instance, one state relevant to the PhD student's work goals might be 'manuscript submitted'. We can now replace $\mathcal{R}$ with local goal functions $\mathcal{G}$, reflecting the personal relevance of reaching certain states identified as goals [82,83]. Such goal functions have a simple shape, providing satisfaction only when a goal is achieved, or, alternatively, incurring costs until a goal is achieved. Goals function like homeostatic set points, but in an abstract space. The person's belief structure $\mathcal{T}$ then encapsulates beliefs about how actions will move them between states. The RL policy π could then be related to the person's self-concept, determining what they believe they tend to do [64]. With this setup, $\mathcal{T}$ defines a graph, defining how behaviours allow progress along the states. $\mathcal{V}$ defines a distance akin to that in the homeostasis example, such that states with higher $\mathcal{V}$ are closer to the goal, and the perceived extent of progress towards the goal is now approximately measured by $\delta\mathcal{V}$ (Box 1) and determined by a person's own belief structure $\mathcal{T}$.

Considering again that progress towards the goal determines hedonic returns, we can now return to our introductory example: Figure 1D–F illustrates the impact of apparently irrelevant goals (work) on subjective experience (food) in close analogy to what we saw in the homeostatic example. The hedonic impact from your favourite food depends on how much it progresses you towards your self-care goal. This progress is more pronounced, and hence it is more pleasurable, when you have had a manuscript accepted and your career goals are satisfied, than after a setback at work. Hence, translating the notion of homeostatic rewards to a conceptual space provides one path whereby the hedonic impact of events, rather than being tied to the primary reward function $\mathcal{R}$ (i.e., to the size of a reward obtained), could be constructed and could be determined by the local estimate $\widehat{\delta\mathcal{V}}$ of progress towards current goals within an individual belief structure $\mathcal{T}$.

The representation of belief structures in the RL framework has an important advantage for our understanding of consummatory anhedonia, in that it allows us to formalise the concept of meaning, with the connections between states in each individual's belief structure enabling the attribution of positive or negative meaning to each state and as a function of how it relates to the goal (c.f. notions such as goal-compatibility in appraisal theories of emotion; [84]) (c.f. Figure 2C-E). Meaning is then formalised as the relationship between the current state and subsequent states with respect to the goal.

Pathways to pathology

Having introduced the core components of the model, we next consider pathways to consummatory anhedonia in this model. All pathways ultimately have the same effect of increasing the distance to the current goal, but do so in different ways. We focus our discussion on anhedonia, however, the proposed framework could also be used to explore other co-occurring symptoms of, for example, depression and anxiety. We start with stress, then turn to appraisals and meaning, and the importance of pathological goal selection.

Multidimensional goal stress

Stressful events often precede anhedonia and depression [85]. Even in the healthy population, acute stress reduces subjective pleasure from rewarding experiences [86]. Neurophysiologically, reward sensitivity is reduced in response to laboratory and real-world stress [87–90], particularly in depression [91].

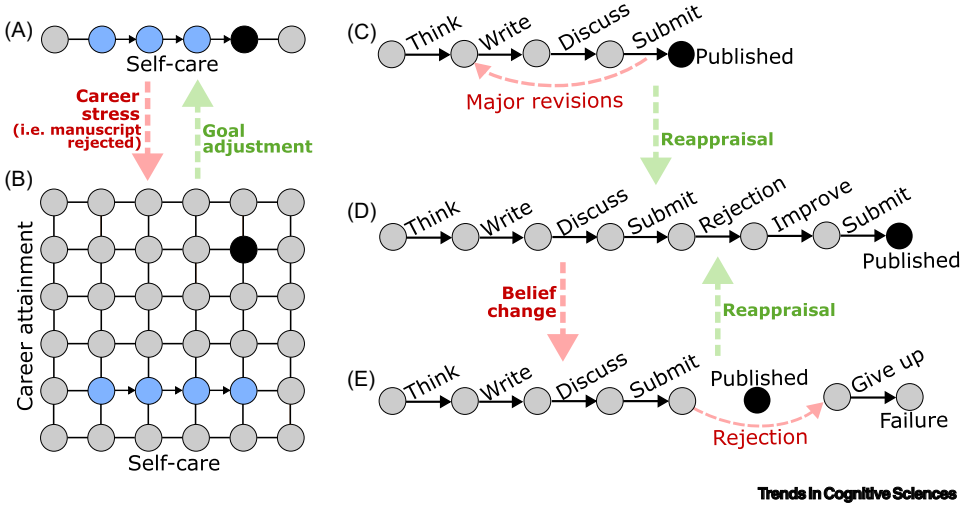

Figure 2. Pathways to pathology. (A,B) Multidimensional goal stress. When the goal involves only a single dimension, such as self-care (A), any movement along this dimension results in clear progress and hedonic experience. However, if we experience a stressful work event, such as the rejection of a manuscript illustrated by the red arrow, this introduces another unrelated dimension, as our goal now involves self-care and submitting a manuscript (B). Movement along the self-care dimension in the multidimensional setting results in less value change (hedonic experience) compared with the unidimensional space, as illustrated in Figure 1 in the main text. To overcome this, the individual could adjust their goal to focus only on one dimension to reduce the state space back to a unidimensional space. (C–E) Stress appraisal. Panel (D) demonstrates an adaptive belief structure for publishing a manuscript. We here depict an example where the student believes there will be an initial rejection of the manuscript, which will help them to improve the manuscript and then have it accepted. Panel (C) illustrates a pathological structure in which the student believes the manuscript will be immediately accepted. In this scenario, rather than the rejection being appraised as another step towards the goal, it moves the student away from the goal and increases the distance. If the student were to reappraise the rejection and alter their belief structure to reflect belief structure (D), the rejection would not elicit a stress response and the revision of the manuscript would elicit a greater hedonic experience. However, if the student with belief (D) encountered an event eliciting a detrimental change in the belief structure to (E), they might predict the manuscript will never be published, represented by the missing transition to the state of 'Published'. In this situation, any work on the manuscript will lack pleasure as it is impossible to progress towards the goal. Reappraisal to represent a possible path to the goal is necessary to experience hedonic returns from the manuscript writing process. Sustained engagement with the multidimensional goal or the pathological belief structure reflects the third pathway to pathology: goal persistence. The less able the student is to flexibly adapt their goal and their belief structure following manuscript rejection, the lower their hedonic experience.

In the model, a reduction in hedonic impact from progress results from increasing the distance to a goal. Clearly, this then distinguishes two different types of stressors. The first is an unrelated stressor, which increases the distance to a multidimensional goal along an orthogonal direction. Figure 2A,B illustrates this. Before the stressful event, the individual's goal was simply to enjoy their favourite food as a form of self-care, whereas following the stressful event their goal consists of both self-care and submitting the manuscript to progress their career. As with the homeostatic example (Figure 1A–C), the presence of an unsatisfied need in another unrelated dimension alters the present state and, subsequently, the hedonic experience of progressing with the manuscript (Figure 1D–F).

The impact of competing goals or other worries has been highlighted in qualitative studies. For instance, adolescents with anhedonia identify the presence of competing goals as issues driving anhedonia [92]. More generally, the relevance of goals to stress is well-established. Stressful events are thought to threaten the maintenance and attainment of important goals [93], and experiences of goal disturbance are associated with psychological distress, especially depression [94,95]. The (much smaller) literature on positive life events in fact supports a key feature of the

model, namely that movements towards goals have the opposite effect [96]. The more important the goals (i.e., the more relevant to a person's core values) [25], the more long-lasting and substantial the effects.

Of course, for an individual to represent every goal they hold would require numerous dimensions and be too computationally demanding. Rather, we suggest that individuals are able to represent only their most pressing goals at any one time in a flexible, low-dimensional space. The challenge and potential pathology arises when an individual considers multiple goals simultaneously, requiring a higher-dimensional representation and subsequent flattening of value changes.

In terms of explaining consummatory anhedonia, this account suggests that the experimental evidence of blunted reward sensitivity in anhedonic participants [19,31–36,39,40] may arise from these individuals thinking about task-irrelevant concerns ('stressors') during experiments. As well as being a common symptom of depression itself, this rumination introduces additional unrelated dimensions, leading to conflict between these multidimensional concerns and maximisation of experimental monetary gains and additionally may impact learning and working memory capacity [97,98].

Pathological stress appraisal and meaning

The second path for a stressful event to reduce hedonic experience in the model is by moving the person away from their goal along the currently relevant dimension. This in turn can happen in different ways. An event could return a person to a distant state; the student may believe the manuscript is ready for publication but the reviewers suggest major revisions. Alternatively, an event can induce a change in the person's underlying belief structure. The value of submitting a manuscript is determined by the predicted consequences of submission: will the manuscript be accepted or rejected. If, as illustrated by the red arrow between Figure 2D and E, an event occurs which leads the student to believe the manuscript will never be accepted, this induced change in their belief structure makes the goal unachieveable, hence submission will elicit no hedonic response.

This view puts strong emphasis on how events are 'interpreted' (i.e., how they are embedded in a changed understanding of the world), in defining a stress response. Belief structures and tendencies to make particular types of attributions are indeed well-established core pathological contributors to stress reactivity [99–101]. Appraisal theories of emotion have identified several categories of appraisals (or interpretations), for instance, goal congruence, achievability, and agency, which lead to specific types of meaning being attributed and, in turn, elicit specific kinds of emotions [84,102,103]. Stressful events can, however, have long-lasting positive or negative effects both behaviourally and neurally [104–106]. The model captures this through the dependence on an individual's belief structure, which allows for events which are profoundly stressful for one person to be highly attractive for another (e.g., the rejection of a manuscript means I have failed, versus that I will eventually publish a more elegant manuscript).

In the model, meaning is defined as the perceived associations between a state and subsequent states. The meaning assigned to outcomes following the stressor therefore depends on the underlying belief structure, which is subjectively constructed and influenced by a number of individual factors. Anxiety, for example, covaries with anhedonia and involves assigning different meaning to events and belief states [107], affecting belief structure and goal distance. The attribution of meaning according to the individual belief structure may also qualitatively explain other aspects of depression, such as hopelessness and suicidal ideation. In the graph of Figure 2E, inachievability is due to missing connections between different parts of the graph. Such a lack

of connection would also be consistent with the reduced sense of meaning in anhedonia [108]. If the individual is unable to adjust the belief structure, persistent engagement in ' meaningless' events and feelings of hopelessness may lead to thoughts regarding whether life is worth living [109].

We note that anhedonia has been extensively related to effort sensitivity [41,42]. The model captures this if we consider that every transition has a fixed cost. An increased perceived distance would then result in an increased expected cost to reach a goal.

Pathological goal persistence

The third pathway to pathology is through the selection and/or maintenance of unachievable goals. There is indeed evidence that sustained engagement with a goal perceived to be at greater distance is associated with higher depression scores [110]; that individuals with depression are less able to disengage from such a goal; and that anhedonia specifically is associated with an inability to re-engage with a new goal [111–113].

Consider again the stressful changes illustrated in Figure 2. Perseverance with the original plan in Panel B (self-care) in the presence of the new goal, would result in small δ and, hence, low hedonic returns. This may best capture the notion of goal ambivalence, which has been linked to risk for depression [114]: completing the original assignment is maintained as a goal, but as it does not address the other goal, its achievement alone is not sufficient. Similarly, persevering with a single goal (publishing a manuscript) that is unachievable under the current belief structure will not elicit any hedonic experience. An inability to flexibly adapt goals or belief structure in response to potentially stressful events may characterise psychopathological consummatory anhedonia.

The process through which goals are selected is poorly understood [76], but it is important to consider the role of this construction process in psychopathology. It may well be that goal selection is a slower, more involved and explicit process, more deeply related to longer-term features of individuals rooted in or defining personality traits.

Value in treatments for anhedonia

Anhedonia is associated with poorer outcomes and has hence been the focus of dedicated treatment research. The model presented allows some reinterpretations of how treatments (fail to) work.

The model suggests that selecting and engaging with achievable and personally meaningful goals, or goals which better align with progress towards the set point, may reduce anhedonia because these will be closer, and assign greater value, to our current state. Several psychotherapeutic approaches, including, amongst others, behavioural activation, acceptance and commitment therapy, and motivational interviewing, all formalise ways of identifying meaningful goals, and then supporting individuals, in pursuing these [25,115]. We recently found that a goal intervention alters effort sensitivity [71], which in turn is related to anhedonia [3] and likely reflects aspects of goal distance. Qualitative work exploring patients' experience also suggests that engaging with goals is perceived as helpful [92]. A promising modification of behavioural activation for anhedonia places greater focus on selecting personally value-congruent behaviours [116], which would further increase the hedonic value of the goal state.

The model also suggests that interventions which focus attention on individual goals (and hence individual dimensions) to directly reduce multidimensional interference may also increase hedonic experience. This reflects the efficacy of interventions which focus on 'in-the-moment' savouring in treating anhedonia, such as positive affect therapy, which combines aspects of behavioural

activation with recounting and savouring pleasurable moments [10,117] and mindfulness-based interventions [116,118,119].

Next, the model suggests that changing the way stressful events are appraised may improve hedonic experience. More specifically, changing an individual's belief structure following an event may enable them to consider alternative paths to goals and assign positive meaning to the involved states. Recent mindset interventions aim to change appraisal of stressful events by teaching individuals to identify the potential gains from events and ones' response to them [120]. These interventions have been shown to effectively reduce negative behavioural and physiological stress responses in adult and adolescent samples and to moderate the association between perceived stress and depression [120–122].

Concluding remarks

Here, we extended the RL account of anhedonia to consummatory aspects. We suggest that the consideration of goals and the notion of progress towards the goals within a model-based RL scheme provides a helpful account of consummatory anhedonia. We identified four key limitations to traditional accounts of anhedonia: inconsistent evidence for a generalised reduced hedonic response to primary rewards, the multidimensionality of hedonic response to complex stimuli, inconsistent neuroimaging support, and the mostly descriptive nature of such accounts. By considering subjective reward, we identified model-based value changes as likely drivers of hedonic experience.

This enabled a novel normative view on prominent phenomena related to anhedonia, including the effects of stress, individual belief structure, and goal-relevance, -selection, and -persistence, none of which had been considered by previous theoretical models. The model also enabled an integrative interpretation of a number of treatment developments aimed specifically at anhedonia. Critically, the model brings clinically relevant consummatory reward processes in humans within the purview of motivational, model-based RL methods, enabling theory-driven studies of alterations in hedonic experience. The model makes clear, quantitatively and qualitatively testable predictions (Box 2), presents new avenues for further mechanistically-driven research (see Outstanding questions), and may also provide directions to explore for novel interventions for anhedonia.

Box 2. Empirical predictions and research implications

The account of anhedonia makes a number of testable predictions in terms of hedonic reactivity, including:

1. **Proximity:** events that move individuals towards or away from their current goal have a positive or negative hedonic impact, respectively. While not directly tested, it is in keeping with the finding that the greater an object's perceived utility to progress towards a goal, the greater the desirability of said object [72].
2. **Beliefs:** the hedonic effect of a change in beliefs is proportional to the extent to which the belief change alters the perceived distance to the goal. This is in keeping with the finding that learning a new task strategy that reduces the distance to a goal increases behavioural and neural representations of the associated value function [123].
3. **Second goal:** introducing a second goal along a different dimension to the first goal effectively increases the distance to the goal and will hence reduce the hedonic impact of progress towards the first goal. Conversely, removal of a second goal will increase the hedonic impact of progress towards the first goal. Recently, such an effect of a second goal has been reported, with the introduction of a second goal reducing the subjective value of progress towards either goal individually [124].
4. **Proximity-dependence of progress:** the same progress at greater distance from the goal will elicit less hedonic impact and a smaller reward prediction error than close to the goal in all three aforementioned situations. This is related to Hull's well-known 'goal-gradient effect'. Indeed, its endless exploitation by apps and customer reward schemes [75,125] suggests that enjoyment and motivation may be inferred quantities, subject to inferential illusions akin to fluency effects [24].

Each of these core empirical predictions have some preliminary experimental support, as indicated, and are all eminently testable. Goals could be introduced by adding additional objectives beyond monetary rewards, or measured by ascertaining individuals' subjective appraisals and relevance of the within-task goals. The core experimental functions are also testable in real-world settings, with the caveat that the true distance to goals cannot be directly measured.

Outstanding questions

Do model-based and model-free RL map onto consummatory and motivational aspects of anhedonia?

How are semantic graphs determining goal distance constructed? Can we identify a neural representation of these belief structures?

What is the process of goal selection, and is there a psychopathological process of goal selection?

Can the process of goal persistence itself be considered in a hierarchial RL framework?

Is a multidimensional goal setting necessarily conscious, or can stress-related goals be maintained and exert effects unconsciously?

Do different neuromodulators have specific roles in goal selection and hedonic experience? In particular, what are the roles of the dopaminergic and opioid systems in these goal-driven reward processes?

The quantities $\mathcal{V}$ and $\delta\mathcal{V}$ can be derived using a variety of algorithms; do these different methods of computing value $\mathcal{V}$ relate to different aspects of anhedonia? For example, can the successor representation better account for the automatic lack of pleasure experienced by anhedonic individuals?

anhedonia treat rewards as if they are not as valuable. However, the mechanism goes beyond an innate 'reward function' and implies a complex construction of subjective hedonic experience that integrates events with an person's goals, aims, and broader 'values'. Treatments for anhedonia may benefit from focusing on changing the process through which valuation occurs and the subjective experience is derived.

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