Goal progress shapes hedonic experience

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1 Abstract

Reward experience guides human behaviour and is essential to wellbeing. Impairments in the capacity to experience reward, such as consummatory anhedonia, have been conceptualised as a fundamental primary hedonic deficit, however there is little evidence to support this view. We previously proposed that hedonic experience instead arises from alterations in the subjective interpretation of events in relation to personally meaningful goals, which we formalise using a Reinforcement-Learning framework. Across three experiments (N=500), including discovery and pre-registered replication studies, we find support for the core predictions of the theory; we show that progress towards individuals' current goals were related to positive hedonic experience in a proximity-dependent manner, with more important goals eliciting a greater hedonic response. Furthermore, manipulating the structure of the underlying belief space affected subjective hedonic experience. These findings suggest that alterations in human hedonic experience may reflect disruptions to more complex evaluative processes.

2 Introduction

Our experience of rewards fundamentally shapes and organises our life, behaviour, and wellbeing. When our experience of rewards is blunted, this has broad repercussions. Anhedonia, or specifically consummatory anhedonia in more recent reconceptualisations, is clinically described as just such an impairment in an individual's capacity to experience rewards (Ribot, 1896; Klein, 1974; **?**). It is seen in numerous illnesses, though most prominently in depression (Trostheim *et al.*, 2020), where it is one of the core diagnostic criteria (American Psychiatric Association, 2013). It is clinically relevant because it is associated with adverse outcomes and poor treatment response (Gabbay *et al.*, 2015; Spijker *et al.*, 2001; Auerbach *et al.*, 2022; Craske *et al.*, 2016).

Clinical conceptualizations of anhedonia such as endogenomorphic (Klein, 1974) or melancholic depression (Parker *et al.*, 1994; Parker, 2007; American Psychiatric Association, 2013) have emphasised a fundamental dysfunction in primary reward capacity and underlying neural circuitry. However, we argue that impairments in hedonic experience may instead arise from alterations to more complex evaluative processes, specifically the subjective interpretation of events in relation to personally meaningful goals (Fig. 1a). We recently formalised this idea in a mechanistic theory of consummatory anhedonia (Hall *et al.*, 2024), proposing that hedonic experience reflects internally generated judgements about progress toward goals.

Consistent with this view, laboratory assessments have long struggled to identify a fundamental deficit in primary hedonic capacity in individuals with anhedonia. Early work (Amsterdam *et al.*, 1987) reported a promising yet fragile correlation between the subjective pleasantness of sweet solutions and anhedonia in the absence of a group distinction between healthy controls and depressed patients. However, this association between anhedonia and subjective pleasantness or pleasure was not replicated later across multiple studies (Berlin *et al.*, 1998; Steiner *et al.*, 1993; Dichter *et al.*, 2010; Clepce *et al.*, 2010; Colle *et al.*, 2020), despite observing alterations in subjective intensity, facial expression, potentially dopamine-sensitive(Kaltenboeck *et al.*, 2022) discriminatory thresholds, and therapeutic response. In contrast, a large number of behavioural and imaging studies (reviewed in Bylsma *et al.* (2008); Husain & Roiser (2018); Borsini *et al.* (2020); Wang *et al.* (2021)) have broadly identified reward circuitry changes in association with anhedonia. Critically, the vast majority of these studies have used more complex or secondary reinforcers, such as money or visual images – precisely those which involve subjective valuation and interpretation.

The absence of consistent evidence for a primary hedonic deficit supports our suggestion that, when individuals with depression express difficulties in the ability to enjoy rewards, these difficulties may not reflect a dysfunction of a primary underlying reward process (Huys *et al.*, 2013), but disruptions in more complex subjective reward evaluations. Indeed, further considerations of reward processes have identified a number of distinct components relevant to anhedonia, including consummatory vs anticipatory processes (Gard *et al.*, 2006), ”liking” vs ”wanting” (Dayan & Berridge, 2014; Dayan, 2022), and effort processes (Treadway *et al.*, 2012; Cooper *et al.*, 2018), among others (Wang *et al.*, 2022). Neurally, improvements in anhedonia involve higher cortical areas (Lally *et al.*, 2014, 2015) associated with computationally refined evaluative processes, rather than primary sensory or hedonic circuits alone. More broadly, the notion of ’primary reward’ remains rather elusive theoretically (Singh *et al.*, 2009). The hedonic value of even primal reinforcers such as sex is determined by complex interpretative models ascribing ”meaning” to events, notwithstanding genetic forces operating at larger evolutionary scales (Dawkins, 2024). In line with this, studies show that altering the meaning of pain has surprising efficacy in chronic, treatment-resistant pain (Ashar *et al.*, 2022), and altering the meaning of stress has long-term consequences for internalizing symptoms (Yeager *et al.*, 2022).

Based on concepts of reinforcement learning (Keramati & Gutkin, 2011), our theory of consummatory anhedonia captures the impact of ”meaning” in terms of internal judgements or interpretations about progress towards goals: events that are interpreted as indicating progress towards goals lead to positive hedonic judgements. The dependence on interpretation renders hedonic judgement sensitive to individual belief structures. The theory, as stated in Hall *et al.* (2024), made four specific predictions (Fig. 1b). Most basically, events that imply more progress towards goals should be judged as more pleasurable. Second, akin to Hull’s goal-gradient effect (Heath *et al.*, 1999; Kivetz *et al.*, 2006), the theory predicts that progress close to the goal should lead to more hedonic response than equal progress far away from the goal. Both of these effects would capture anhedonia in response to life events or chronic stress, where important goals are judged unachievable. Third, changes in belief structure should affect hedonic judgements to the extent that they alter perceived goal distances (c.f. Cortese *et al.* 2021). This would capture the impact of changes in interpretation e.g. as a consequence of cognitive therapy, on hedonic capacity. Fourth, the introduction of a second goal should also reduce the hedonic impact of goal progress because a second goal effectively increases goal distance. This enables the theory to explain why *prima facie* unrelated events (e.g. life events such as job losses) affect hedonic capacity broadly.

Here, we provide support for this theory across three different experiments, spanning self-report and behavioural designs, 500 individuals, and discovery and pre-registered replication studies. All four hypotheses were supported: In both self-report and task-based designs progress towards individuals’ current goals were related to positive hedonic experiences; and equivalent progress at a greater distance from the goal elicited a less positive hedonic experience than closer to the goal. Progress towards more important goals had greater hedonic impact; the structure of the belief space affected progress ratings and subjective judgements, and introducing a second (irrelevant) goal reduced hedonic responses. Anhedonia, depression and hopelessness had the hypothesized effect on goal distances.

3 Results

Data were collected through three separate studies using different designs: a self-report study, and two task-based studies - a maze game, and a food service game (Fig. 1). Each study was conducted with two independent samples for replication purposes, and will henceforth be referred to as the 'initial' and 'replication' samples. We here present results from the pre-registered replication sample, but note that all findings are consistent with those from the initial sample, which can be found in the Supplementary section **??**.

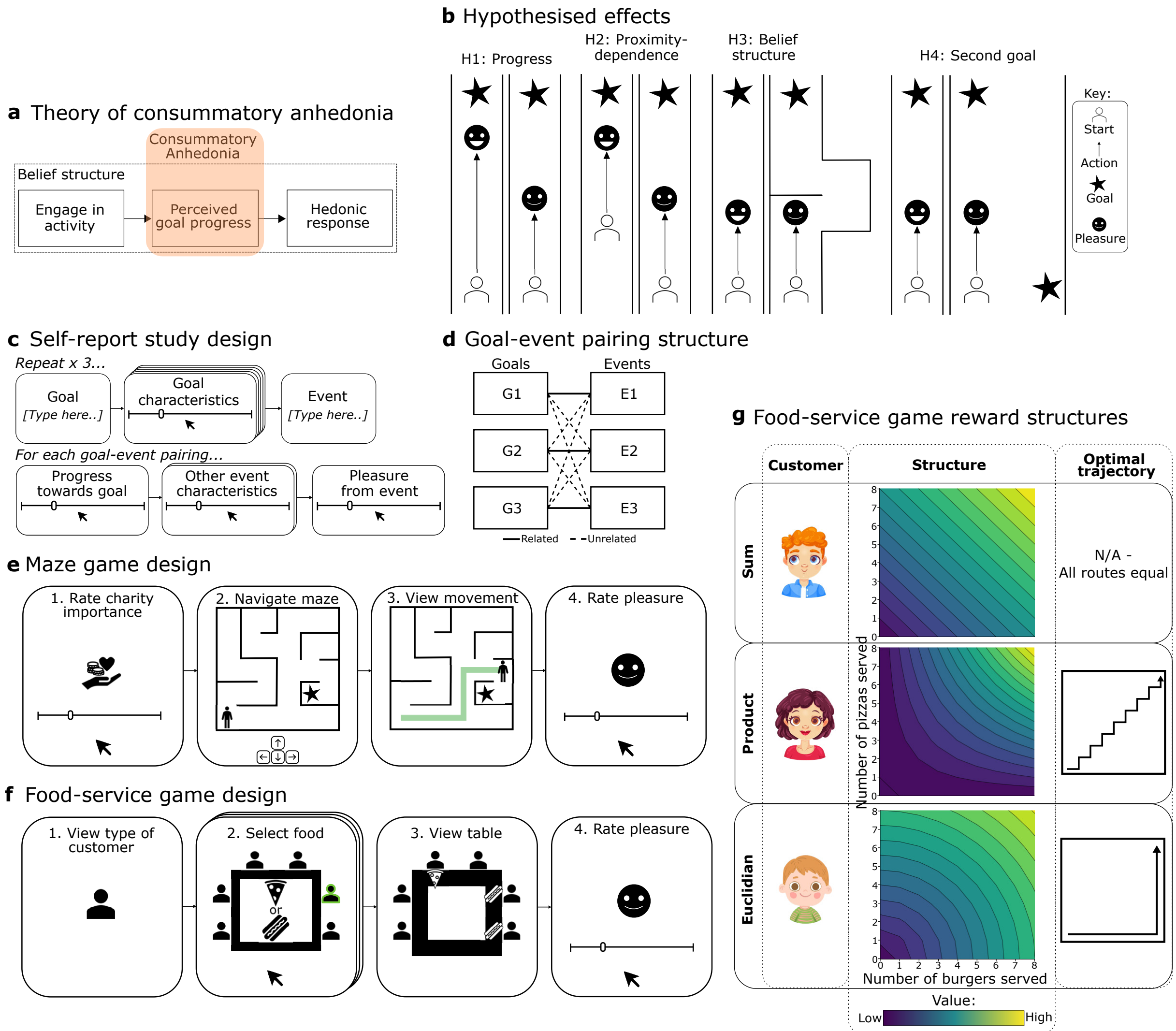

Figure 1: **Hypotheses and task designs. a,** Schematic of our proposed theory of hedonic experience. We suggest that the progress the individual perceives to have made towards their goal, which is influenced by their underlying subjective structure of the environment, determines hedonic experience. We argue that consummatory anhedonia results from an alteration in perceived goal progress, represented by the orange highlight. **b,** Schematic of the four predictions laid out in Hall *et al.* (2024) and tested here. Each pair illustrates a prediction with a more pleasurable (left) and less pleasurable (right) example. **c,** In the self-report study, participants first provide a free-text personal goal, and answer several questions about the goal, before providing a free-text event which they believe would help them progress towards the goal. This is repeated for three goals to generate three goal-event pairings, then each goal and event is repaired, as shown in **(d)**. For each pairing, participants are asked about the progress they would make towards each goal given the event occurring, and the pleasure they would experience from said event. **e,** In the maze game, participants must collect resources in a warehouse to obtain a charitable donation. On each trial, participants are asked to rate how important they believe it is to support the current charity. They then have several seconds to navigate the maze using the arrow keys, before they are stopped, reshown their journey, and asked to rate the pleasure they experienced from playing the game. **f,** In the food-service game, participants are servers in a restaurant. They are told that there are three different types of customer, each who prefer to be served in a specific way **(g)**. On each trial, participants are first shown the type of customer they will be serving. They click on a food to serve it to the highlighted customer, and continue this until they are stopped after several clicks, shown the state of their table, and are asked to rate the pleasure they experienced from playing the game. On some trials, only one food type is available, forcing the participant to take a non-optimal trajectory (see Section 5.3.4 for full details). **g,** Participants are introduced to three types of customer in the food-service game. Each customer represents an underlying sum, product, or euclidian distance relationship between the two dimensions. These give rise to different optimal trajectories through the service space, and participants learn these as 'service preferences' at the start of the task.

3.1 Hedonic experience and goal progress

The first prediction, core to the theory, is that pleasure is experienced from perceived progress towards a goal. Events or actions that result in greater progress towards a goal should elicit greater judgements of pleasure.

We first conducted a self-report study to establish this relationship in its simplest terms (Fig. 1c). Participants provided a series of individually relevant goals, and events deemed beneficial in achieving each of the individual goals. They then provided judgements about how much each event was likely to move them towards or away from each of the goals. Finally, they indicated how much pleasure each event would elicit. Fundamentally, if greater progress towards a goal results in greater pleasure, then there should be a positive relationship between the judged amount of progress an event implies towards a goal, and the subjective report of pleasure. There was a significant and positive relationship between the extent of perceived goal progress elicited by an event and the subjective pleasure experience induced by the event (Fig. 2a, $\beta = .007, SE = .0007$, 95% CI $[0.007, 0.018]$, $t(39.550) = 10.147, p < .001$). Critically, this relationship also held when examining the effect of events on progress towards the unrelated goals (Fig. 1d), i.e. the goals for which other events had been generated (Supplementary Fig. **??**).

Events, goals, and the judged progress were all generated by participants in the self-report study. While this shows that there is consistency even between events not intentionally related to goals, it cannot be excluded that the pleasure and progress judgements were generated in some correlated manner by individuals. We therefore designed two new games to experimentally manipulate and objectively measure progress.

The first new game was a simple maze game. Solving mazes is a game enjoyed by people of all ages and cultures, and in our version participants simply navigated a character around a maze to reach goal states of varying relevance to the subject (Fig. 1e, Section. 5.3.3). The game was interrupted at random times to assess pleasure, enabling us to assess the relationship between objective progress and subjective pleasure. Local progress towards the goal (Eq. 8) predicted subjective pleasure experience on that trial (Fig 2b, $\beta = 1.069, SE = .056$, 95% CI $[.958, 1.179]$, $t(92.439) = 18.95, p < .001$). This model of progress as a change in state value was significantly superior to that of progress as a change in euclidian distance (ΔBIC=1370.84). In addition, there was a significant interaction between goal intrinsic reward and progress: greater pleasure was experienced from progress towards goal states deemed more important (Fig 2d; $\beta = .009, SE = .001$, 95% CI $[.006, .011]$, $t(5.195) = 7.264, p < .001$).

The second new game was a food-service game where participants were asked to serve foods to customers in a restaurant. The food-service game enabled us to introduce a second, independent goal; to independently manipulate progress towards each of two goals (Fig. 1, Section. 5.3.4); and to manipulate the belief structure. Local progress towards each goal again significantly predicted subjective pleasure experience from the relevant trial (Fig 2c; $\beta = .909, SE = .076$, 95% CI $[.759, 1.058]$, $t(10950) = 11.933, p < .001$). This was true for trials with only one goal (so-called 'one-dimensional structure') and for trials with two simultaneous goals (so-called 'two-dimensional structures') (Supplementary Fig. **??**).

3.2 Proximity-dependent goal progress

The second prediction by the model is that the hedonic response to progress will be dependent on the proximity to the goal; progress that is made when closer to the goal should usually elicit a greater hedonic response compared to equal progress when further away from the goal.

In the maze game and food service game, we computed progress in both absolute (Eq. 7) and local (Eq. 8) terms. If the data are better explained in terms of absolute progress, this would suggest progress is equally pleasurable at any distance to the goal, whereas if the data are better fit by local progress, this would suggest progress is more pleasurable when closer to the goal. In the maze game, we found that the model predicting pleasure as a function of local progress demonstrated a better fit to the data than those predicting pleasure as a function of absolute progress (ΔBIC=3064). Similarly, the local progress model

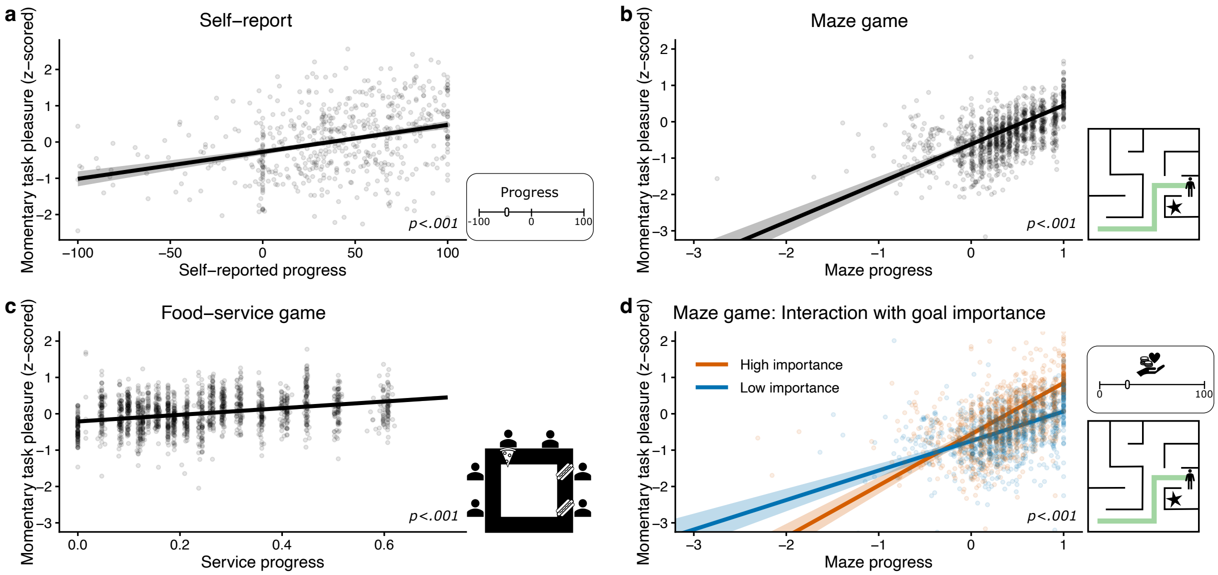

Figure 2: **Momentary pleasure is elicited by progress towards the current goal.** **a,** Participants' self-reported pleasure from an event as a function of the perceived goal progress elicited by said event. Progress was measured through self-report. Points represent per-subject quantile-binned means (computed for visualization only). Solid lines show population-level fixed-effect predictions from a linear mixed-effects model with random intercepts and slopes, and shaded regions indicate ±95% confidence intervals. **b,** Participants' self-reported pleasure from playing the maze game as a function of progress made towards the current goal. Progress was formalised as trial-wise change in maze state value (Eq. 8). Points represent per-subject quantile-binned means (computed for visualization only). Solid lines show population-level fixed-effect predictions from a linear mixed-effects model with random intercepts and slopes, and shaded regions indicate ±95% confidence intervals. The x- and y-axes are truncated for visualization due to several extreme values, but the model is estimated using the full data range. **c,** Participants' self-reported pleasure from playing the food-service game as a function of progress made towards the current goal. Progress was formalised as trial-wise change in table state value under the current reward structure (Eq. 8). Points represent per-subject quantile-binned means (computed for visualization only). Solid lines show population-level fixed-effect predictions from a linear mixed-effects model with random intercepts and slopes, and shaded regions indicate ±95% confidence intervals. **d,** Points represent per-subject, per-condition quantile-binned means (computed for visualization only). Solid lines show population-level fixed-effect predictions from a linear mixed-effects model including the interaction between goal progress and goal importance. Predictions are shown at -1 SD and +1 SD of goal importance (relative to its sample mean). Shaded regions indicate ±95% confidence intervals around the fixed-effect predictions.

demonstrated a better fit in the food service game (ΔBIC=162), and this held for the one-dimensional and all two-dimensional structures (Supplementary Section **??**).

3.3 Belief structure and goal dimensionality

The third prediction is that changes in the underlying belief structure impact hedonic response, in that changes which increase subjective goal distance should reduce hedonic response from progress and vice versa for changes which increase goal distance.

To study the impact of the belief structure, we asked whether subjects were sensitive to the specific structure of the space in which they were progressing. The food service game allowed us to introduce a simple two-dimensional goal and reward structure. Participants were instructed to maximise the happiness of their customers by attempting to serve a predetermined number of two food items within the allotted time, and the reward obtained (here, the happiness of the customers) was dependent on the participant's state (the number of each food item served) within this two-dimensional matrix. We altered the geometry of the two-dimensional structure, manipulating how events related to each of the two goals: movement along one dimension at any state resulted in a different change in reward depending on the structure in which the subject was progressing (Fig 1g). We focus on the product and euclidian structures which display contrasting relationships between the two dimensions.

Qualitatively, participants demonstrated behavioural sensitivity to the belief structure in which they were progressing; when allowed to move through the space freely, most participants served the items along the optimal trajectory for each of the product and euclidian structures (Supplementary Fig. **??**). Quantitatively, if pleasure is predicted by progress as defined by the true underlying structure, then the regression coefficients from a joint model (Eq. 12) for structure-congruent progress terms should be larger (more positive) than those for incongruent terms. In other words, progress computed under the reward structure that generated the outcomes should explain more variance in pleasure than progress computed under alternative structures. Participants were sensitive to the reward structure of the two-dimensional space (Fig. 3a). Specifically, in product-structured blocks, pleasure was more positively associated with product-based progress than with euclidean progress ($\beta_{product} = .134$ vs. $\beta_{euclid} = -.054$; $p < .001$). In euclidean-structured blocks, this pattern reversed ($\beta_{product} = -.102$ vs. $\beta_{euclid} = .171$; $p < .001$). This structure-congruent pattern was observed for every participant when considering individual random slopes (Fig. 3b).

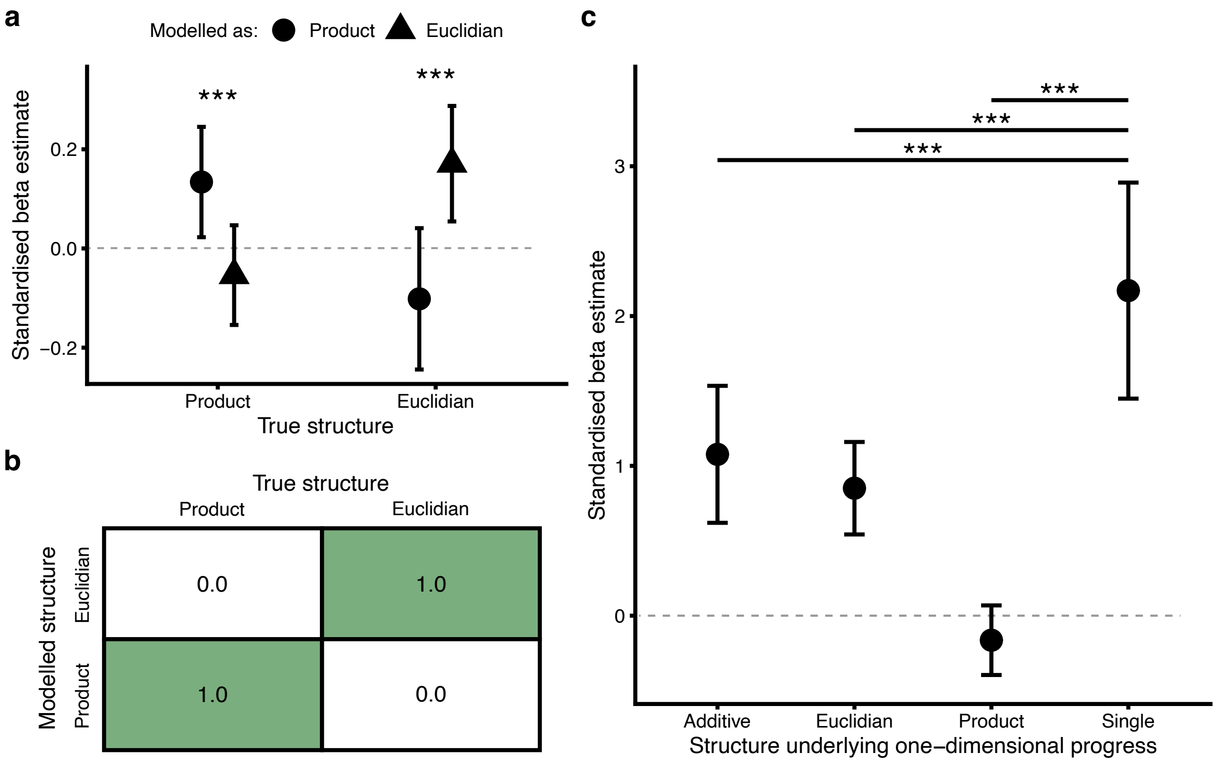

Figure 3: **Sensitivity to reward structure and increasing goal dimensionality.** **a,** Estimated fixed-effects β coefficients from a joint mixed-effects linear regression model predicting pleasure from progress made with respect to each reward structure (Eq. 12), with ±95% confidence intervals. Greater (more positive) beta estimates represent stronger positive associations, as hypothesised, between structure-specific progress and experienced pleasure. $^{***}p < .001$. **b,** The confusion matrix summarizes individual structure-specificity through participant-level random-slope estimates from the mixed-effects model plotted in **(a)**. For each participant, in each structure, we identified the reward structure (product or euclidian) whose corresponding progress term showed the largest positive association with pleasure. Cells indicate the proportion of participants whose pleasure was most strongly predicted by progress in each structure within each true structure. Diagonal (green) entries reflect congruence between the predictive structure and the true reward structure. **c,** Estimated β coefficients from a series of mixed-effects linear regression models predicting pleasure from one-dimensional progress in the single (one-dimensional) structure and each of the two-dimensional structures, with ±95% confidence intervals. Greater (more positive) beta estimates represent stronger positive associations, as hypothesised, between equivalent one-dimensional progress and experienced pleasure. $^{***}p < .001$.

The final prediction made by the theory is that the introduction of a second goal reduces the hedonic impact of progress towards an initial goal as this increases the distance to the now multi-dimensional goal. We considered trials in the food service game from the 'single' uni-dimensional goal structure (i.e. trials in which subjects were instructed to only serve one food item) alongside trials in which uni-dimensional progress was made within the two-dimensional structures (i.e. subjects were instructed to serve two food items but had only served one item). If pleasure is reduced from the introduction of a second goal, one-dimensional progress in the two-dimensional structures should predict a reduced change in pleasure compared to one-dimensional progress in the singular structure. As predicted, analyses revealed that one-dimensional progress in all two-dimensional structures was associated with significantly reduced pleasure experience compared to equivalent progress in the one-dimensional structure (Fig 3c; $\beta_{sum} = 1.077$, $\beta_{product} = -.165$, $\beta_{euclid} = .851$ vs. $\beta_{single} = 2.169$, all $p < .001$).

3.4 Increased goal distance in psychopathology

In a final exploratory analysis, we asked whether the endorsement of anhedonic and related symptoms was associated with differences in goal characteristics reported in the self-report study. The theory suggests that anhedonia may be experienced following an increase in goal distance, resulting in a perceived reduction in local progress. PVSS, PHQ and BHS scores were unsurprisingly highly correlated (Supplementary Fig. **??**), however we found that self-reported anhedonia, depression and hopelessness were all associated with greater subjective goal distance (Fig. 4; PVSS: $\beta = -.265, SE = .071$, 95% CI $[-.404, -.126]$, $t(871) = -3.745, p < .001$, PHQ: $\beta = 1.250, SE = .295$, 95% CI $[.670, 1.830]$, $t(871) = 4.231, p < .001$, BHS: $\beta = 1.566, SE = .296$, 95% CI $[.984, 2.147]$, $t(871) = 5.283, p < .001$).

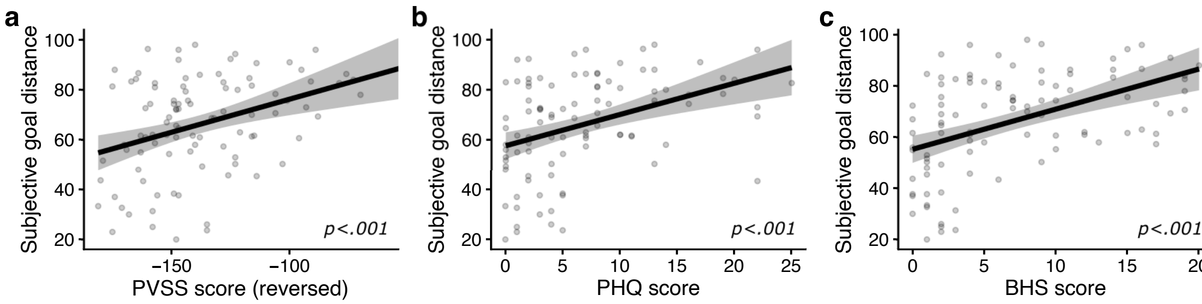

Figure 4: **Anhedonia and related symptoms are associated with increased self-reported goal distance.** Participants' self-reported subjective goal distance as a function of self-reported symptoms of **(a)** anhedonia (PVSS score, reversed for interpretability), **(b)** depression (PHQ), and **(c)** hopelessness (BHS). Points represent subject averages (computed for visualization only). Solid lines show population-level fixed-effect predictions from a linear mixed-effects model with random intercepts, and shaded regions indicate ±95% confidence intervals.

As the other game studies explicitly manipulated the goal distance and progress, the theory made no strong predictions regarding clinical associations in these studies.

4 Discussion

Across three experiments, we found convergent evidence that pleasure was related to perceived progress towards valued goals. Progress more proximal to goals elicited stronger hedonic responses than equivalent progress further away, and pleasure depended on the underlying structure of the goal space. Increasing goal distance by introducing a second goal reduced hedonic impact, and anhedonia and related symptoms were associated with increased subjective goal distance. Together, these findings support the view that hedonic experience arises from inferred goal progress, as proposed in (Hall *et al.*, 2024). It suggest that a path towards clinical symptoms of anhedonia may similarly be through goal progress judgements, rather than necessarily involving a primary deficit in the capacity for reward.

Related research on momentary wellbeing proposes that happiness reflects a running average of reward expectations and resulting prediction errors (Rutledge *et al.*, 2014; Eldar *et al.*, 2016; Bennett *et al.*, 2022; Keren *et al.*, 2021). The models align with the suggestion that momentary affect is related to differences in values, but focus on objective task-defined expectations without consideration for the role of cognitive inference in determining what is valuable to the individual. The present study extends this line of work by showing that momentary pleasure depends on subjective inferences about goal structure and distance, which assign meaning and value to state transitions. Situated within our theory of anhedonia (Hall *et al.*, 2024), we demonstrate that the subjective assessment of progress toward personally valued goals plays a central role in determining hedonic experience, and that disruptions in these inferences are associated with diminished pleasure. This offers a substantial advancement over previous accounts by identifying meaningful, goal-dependent variables that determine subjective value and hedonic experience rather than relying on objective task-specified value signals.

These results align closely with recent theoretical accounts of hedonic experience as a form of potential-based shaping (Dayan, 2022; Ng *et al.*, 1999). In RL, a potential function Φ assigns an additional value to each state to reflect its prospective value. When an agent moves between states, the shaping reward it receives computes to the difference in this potential $\Phi(s') - \Phi(s)$, rewarding transitions toward higher-valued states and punishing the reverse. Potential-based shaping therefore acts to facilitate learning by augmenting (potentially sparse) ”true” rewards, or providing a scalar quantity through an estimate of meaning and significance in environments where no external reward is present (Keramati & Gutkin, 2014; Lieder *et al.*, 2019; Dayan, 2022). Dayan (2022) suggest that ”liking” communicates this preliminary estimate of the long-run value to the individual; hedonic values guide the individual towards more favourable decisions to reach the desired state or goal more efficiently than if they were to rely on slow learning signals. In our framework, distance from the goal may serve as a proxy to the potential, and ’perceived progress’ simply operates as a qualitative term for the shaping function, conveyed to the individual through the pleasure experience. Indeed, a distance-heuristic has been suggested to be a sensible approach to determining potentials (Ng *et al.*, 1999). Participants in our simple tasks may have learned or inferred the structure of this goal space, with pleasure reflecting the accuracy of those inferences. In more complex or ambiguous environments, such shaping signals may rely increasingly on approximations and subjective beliefs and meaning, providing a route through which personal goals and values determine hedonic experience.

Pleasure derived from food consumption, which has been studied in greater detail, as well as aesthetic experience can be understood within the same potential-based shaping framework. In the domain of primary food rewards, ”liking” and ”wanting” dissociate into distinct computational and neurobiological processes (Berridge & Robinson, 2003; Dayan, 2022). Novel methods dissociating the immediate sensory experience during food consumption from the downstream digestive processing and nutritive assessment consistently support this separation (Sclafani, 2001, 2013; De Araujo *et al.*, 2008); the influence of food on ”wanting” processes is slower and assessed by different neurobiological circuits than those related to ”liking”, yet (if we are to consider food as a primary reward related to survival) it is the long-term nutritive value of foods that guides animal behaviour, and ”wanting” rather than ”liking” has been shown to underlie maladaptive behaviours such as over-eating and substance use (Berridge & Robinson, 2016; Morales & Berridge, 2020). Dayan (2022) suggests that food palatability acts as a potential function, allowing ”liking” to shape behaviour and increase the speed of learning compared to the slow digestive process. A similar logic applies in the aesthetic domain, where the potential corresponds to the efficiency of one’s internal generative model of sensory inputs. As shown by Ryali *et al.* (2020), stimuli that are statistically typical—that is, more likely under the individual’s internal model—are also judged more likable, consistent with ”liking” tracking local improvements in model fit or processing fluency (Brielmann *et al.*, 2024). This resonates with the idea that reward is defined by the agent’s internal state and model of the environment rather than external environmental signals, and illustrates how pleasure communicates inferred progress toward a valued physiological equilibrium or sensory system.

More broadly, the view of consummatory anhedonia outlined here reconciles clinical conceptualisations of anhedonia with studies finding inconsistent deficits in sensory reward experiences in anhedonia (Colle *et al.*, 2022; Atanasova *et al.*, 2010; Kohli *et al.*, 2016). The suggested resolution is that the sensory experience remains intact and that instead the internal model, or more specifically approximations of the potential, underlie diminished pleasure. The current study supports this suggestion in that altering the belief structure to increase goal distance diminished pleasure, and self-reported anhedonia was associated with such an increase in distance to real-world goals. We highlight the important role of stress, which is commonly associated with reduced reward responsiveness and anhedonia: experimentally, acute stress has been shown to decrease reward responsiveness and hedonic capacity (Berenbaum & Connelly, 1993; Bogdan & Pizzagalli, 2006), longitudinal studies have shown that naturalistic stressors reduce reward learning in individuals with anhedonia (Min *et al.*, 2024), and reductions in perceived stress predict improvements in anhedonic symptoms in both psychotherapy and antidepressant treatment (Phillips *et al.*, 2023). We suggest that stress may lead to anhedonia by increasing the perceived distance to the goal (Hall *et al.*, 2024), whether that be through impacting the individual’s ability to accurately approximate the potential function or through changing the individual’s internal model. Existing effective treatments for anhedonia, such as Behavioural Activation (Jacobson *et al.*, 1996; Martell *et al.*, 2010), Positive Affect

Therapy (Craske *et al.*, 2023), ADepT (Dunn *et al.*, 2023), and Mindfulness approaches (Cernasov *et al.*, 2021; Garland *et al.*, 2021; Carlton *et al.*, 2022), directly involve consideration of goal structure and the importance of perceived stressors and motivations. It may be insightful to consider the effect of such therapies within the proposed framework more directly, as well as the potential effects of dopamine and NMDA receptor targets within a goal-based value framework.

There are several limitations to the current study. The absence of a clinical population limits the conclusions that can be drawn about the mechanisms of anhedonia, and future work should test this account directly in clinical samples. Although our tasks have not been formally validated, no existing paradigms address our specific research questions and the replication of key effects across samples nonetheless supports their reliability. Each task incorporated an explicit goal, assuming participants internalised it during performance. This design was necessary to quantify goal progress, but may only partially capture the self-generated goals that our account emphasises as central to hedonic experience. Participant feedback suggested that task goals were indeed internalised, though the broader process of goal selection remains poorly understood. Understanding how individuals identify and prioritise goals will be crucial for applying this framework to more naturalistic contexts.

In conclusion, hedonic experience is associated with progress toward personally valued goals, possibly acting as a potential-based shaping signal which guides behaviour in the absence of explicit rewards. Conceptualising anhedonia as a disruption in this internal goal-dependent representation reframes it as a disorder of subjective value representation rather than of sensory reward sensitivity, offering a unifying framework linking reinforcement learning, affective experience, and clinical anhedonia and offering mechanistic insights into the disorder and its treatment.

5 Methods

5.1 Ethical approval

All studies were approved by the University College London Research Ethics Committee (project ID 16639/001). All subjects gave online informed consent.

5.2 Participants

For all studies, subjects were recruited online from the participation platform Prolific (www.prolific.com). Subjects were required to be based in the UK, aged 18 to 70 years old, fluent in English, and at least 95 percent approval rate on Prolific. Subjects who did not fully complete the study were excluded on exit and recruitment continued until the target number of subjects had fully completed the study.

The samples for both the initial self-report study and initial maze game each consisted of fifty individuals. One subject from the self-report study was excluded due to missing data, resulting in a final sample of 49 individuals (25 male, aged 19 to 70 years, mean 46.2 years). All fifty subjects were included in the maze game (25 male, aged 22 to 69 years, mean 36.5 years). 100 individuals were recruited for the initial food service game. One subject was excluded due to missing data, resulting in a final sample of 99 individuals (50 male, aged 19 to 58 years, mean 34.6 years).

One hundred individuals were recruited for each replication study. Several participants were excluded from each sample due to missing data, resulting in a sample of 100 subjects in the self-report study (50 male, aged 19 to 70 years, mean 41.2 years), 95 subjects in the maze game (46 male, aged 18 to 68 years, mean 40.4 years), and 96 subjects in the food service game (48 male, aged 19 to 60, mean 36.8 years).

5.3 Study design

All studies were coded in javascript using the jsPsych library, version 7.3, and conducted online.

5.3.1 Clinical questionnaires

At the start of the self-report study, subjects completed a series of self-report questionnaire measures to provide information on anhedonia symptoms, as well as related mental health symptoms.

In the initial sample, the Temporal Experience of Pleasure Scale (TEPS) (Gard *et al.*, 2006) was used to assess symptoms of anhedonia, distinguishing anticipatory and consummatory pleasure. We also used the Apathy Evaluation Scale to (AES) (Marin *et al.*, 1991) to measure apathy across behavioural, cognitive, and emotional domains of motivation and the Self-report Depression Scale (SDS) (Zung, 1965) to measure symptoms of low mood as these are thought to be overlapping concepts with anhedonia. In the replication sample, the TEPS was replaced with the Positive Valence Systems Scale (PVSS-21) (Khazanov *et al.*, 2020) which measures a broad range of reward-related behaviours more relevant to the healthy population and aligns with the National Institute of Mental Health (NIMH) Research Domain Criteria (RDoC) project (Insel, 2014). The Patient Health Questionnaire (PHQ-9) (Löwe *et al.*, 2004) was used to measure symptoms of low mood instead of the SDS to reduce study time for subjects whilst maintaining validity, and the Beck Hopelessness Scale (BHS) (Beck *et al.*, 1974) was added to measure symptoms of hopelessness, another important overlapping symptom with anhedonia.

5.3.2 Self-report study

In the self-report study, subjects were first asked to report the three 'biggest' goals they currently hold which they have not yet achieved in a free-text response. A description of 'goals' was provided to increase valid responses (see Supplementary Section **??**). For each goal, subjects were presented with a series of likert scale questions regarding goal characteristics: the current duration they have held the goal (0 - "It is brand new" to 100 - "I've had it for an extremely long time"), the progress previously made towards goal achievement (0 - "No progress at all" to 100 - "A huge deal of progress"), the motivation to achieve the goal (0 - "Not at all motivated" to 100 - "Extremely motivated"), the intrinsic reward of goal achievement (0 - "Not at all rewarding" to 100 - "Extremely rewarding"), and 'subjective' and 'objective' current goal distance (0 - "It feels extremely close" to 100 - "It feels extremely far away", and "Within several days" to "Longer than several years", respectively). When considering each goal in question, subjects were asked to try not to compare with other goals or situational factors. For each goal, subjects were then asked to report one realistic event which would be most helpful in progressing them towards the goal in a free-text response, before being presented with another series of likert scale questions: the extent of progress towards the goal elicited by the event (0 - "No progress at all" to 100 - "Progress to full goal achievement"), the distance of the goal after the event (0 - "It would feel extremely close" to 100 - "It would feel extremely far away"), and the pleasure they would experience from the event occurring (0 - "No pleasure" to 100 - "Extremely pleasurable"). The exact wording of the subjects' self-reported goals and events were used throughout the study. Each goal and event were then re-coupled pairwise and characteristic questions repeated for each goal-event pairing, resulting in nine observations for each subject. For the re-coupled pairings, the scale for the extent of progress towards the goal elicited by the event was extended to a minimum of -100 ("Extremely further away") as events reported to aid progress towards one goal may have negatively impacted progress towards another goal.

Several small alterations were made to the study design following the initial study. In the replication study, the labels associated with the extent of progress towards the goal elicited by the event (-100 - "Full negative progress - goal feels impossible" to 100 - "Full positive progress - goal achieved") and the pleasure experienced from an event occurring (100 - "The most pleasure I've ever experienced") were changed to minimise ceiling effects. The scale for the pleasure experienced from an event occurring was also extended to a minimum of -100 ("The most displeasure I've ever experienced") to better assess the effects of negative goal progress.

5.3.3 Maze game

The maze game involved navigating a maze to reach a goal state at which money was donated to a charity. Subjects were first shown the icons of five well-known charities, as well as the outline of a person to represent themselves, and asked to order them according to how much they would like to earn money for each cause. Subjects were given the opportunity to ask for proof of charity donation following study completion to provide reassurance that this was not simply a cover story and increase validity of the goal reward. Subjects were given the story that a small robot character - the Charitable Asset Retrieval Engine (CARE) - works in a warehouse to collect resources for different charities and he needs some help to find all the resources. First, he needs to carry out his morning checks, which represent a practice period. Subjects were shown a 10x10 maze and instructed to navigate CARE to a check location, indicated by a star, using the keyboard arrow keys. They were told that they would receive a bonus for every star reached. Subjects were given as much time as they required to navigate to the goal state, after which the star disappeared and reappeared in a new goal location. This repeated for two practice trials.

For the main task, subjects were told that CARE has moved to a new warehouse where he collects resources for charity as well as tips which would be converted to bonus earnings. The goal state now appeared as a brown crate, and each one represented a different charity towards which they would earn a donation. At the start of each block, subjects were told which charity they would be working towards and asked to rate, on a scale of 0 (”Not at all important”) to 100 (”Extremely important”), how important they felt it was to support that charity. The trial began and they were given six seconds to navigate as far as possible towards the goal location. The screen was then frozen for five seconds and subjects were shown their ’journey’, represented by a green line through the maze from their start to CARE’s current location, before they were asked ”How much pleasure did you experience from this period of game play?”, on a scale from -100 (”A great deal of displeasure”) to 100 (”A great deal of pleasure”). The scale extended to -100 to account for negative progress. Together, this formed a single trial. This trial structure (navigate, view journey, pleasure rating) repeated, with the robot continuing from the state in which they previously stopped, until the goal was reached. Charity rating, followed by trials until goal achievement, formed a single block. Blocks were repeated twice for each charity as the goal, resulting in 12 blocks for a single maze. The starting and goal positions were predetermined and identical for each subject - these were initially closer together to encourage goal achievement and become further apart in later trials to increase the variation in progress. The first 12 blocks took place in a 13x13 maze, followed by a further 12 blocks in each of a 17x17, 20x20 and 25x25 maze. The time limit for navigation increased with maze size, from six, to seven, eight, and ten seconds, respectively. The trial and block order were consistent between subjects, however the specific charity representing the goal was randomised within mazes.

The design of the maze game remained almost identical in the replication game. The only alteration made was to swap out two of the charities for less popular, more divisive charities to maximise the potential effects of goal importance on pleasure experience.

5.3.4 Food service game

The food service game was used to introduce a two-dimensional goal. Subjects were told that they are a server in a busy restaurant and must serve as many customers as possible to make them happy before their shift ends. Subjects were shown a simple visual illustration of eight sad-looking individuals sat around a table. A silhouette image of a pizza would randomly appear in front of one of the customers, with a number on top representing the number of pizzas remaining to be served, and subjects were told they must click the pizza image to serve it to the customer. Once they had served the customer, the character became visually happy. Subjects were told to work as quickly as possible to serve the customers before the time ran out, which was represented by a circular countdown in the centre of the screen. Unbeknownst to subjects, the time was manipulated to allow them to only feed a subset of customers (the ’customer limit’), which was fixed on each trial. Several times throughout the trial, the task was paused, they were shown how many people they had successfully served, and asked ”How much pleasure did you experience from the previous period of game play?” on a scale from 0 (”No pleasure at all”) to 100 (”A great deal of pleasure”). The scale did not cover the negative range as negative progress was not possible in this game. This structure, consisting of serving the pizzas, viewing progress, and a pleasure rating, formed one trial. The trial structure repeated, with service resuming at the state in which it was previously paused, until the customer limit was reached. All trials for one ’service’ formed a block, and this block structure repeated for 10 services.

Subjects were then told that the restaurant had been taken over by a new owner who wished to serve burgers as well as pizzas. Their task was still to make the customers as happy as possible by feeding them all before the shift ends, but they would now have to manage 16 customers in a single service, with eight individuals wanting pizza and another eight wanting a burger. The introduction of eight individuals requiring a different food represented the second dimension, and we aimed to explore how different interactions between the dimensions, creating different state space structures, would affect behaviour and pleasure experience. Specifically, we manipulated the two-dimensional reward structure to be either the sum, product, or euclidian distance of the two dimensions (see Section 5.4). To simplify understanding of these structures, subjects were told that they would, respectively, serve either teenage boys, young women, or children, who had specific service preferences; the teenage boys were simply hungry and would take whichever food they were given, the young women preferred to share food so should be served pizza and burger alternatively, and the children preferred to copy each other so should be served all of the same food followed by all of the other. These preferences represented the optimal paths through each structure (Fig. 1g).

Following these instructions, subjects were told which customer they would be serving and then shown the table illustration again but now both a pizza and burger silhouette appeared in front of a random customer, with the respective number of each remaining printed on top of the silhouette, and subjects had to click on one food to serve it (Fig. 1f). The customers took the form of either a child, teenage boy, or young woman. As before, the customer became visually happy after being served, but more so if subjects had chosen the optimal food. The task began with one practice block for each reward structure, in which a green outline appeared around the optimal food choice to aid subjects in their understanding of the game. The following blocks would continue without aid, with pleasure ratings at intervals throughout a block and a predetermined customer limit to each block. Each block would begin by informing the subject which type of customer they would be serving and provide a reminder of their 'preference'. Furthermore, subjects were also told that sometimes the kitchen would become overloaded and could only create one food at a time. On these trials, one of the two food choices would appear faded out to represent that it was unavailable. The structure of these trials was manipulated to ensure that subjects followed all possible trajectories and provided pleasure ratings throughout the state space.

The main task consisted of 36 blocks, with each reward structure represented in 12 blocks. The order of blocks was consistent between subjects and at least two blocks of the same reward structure followed consecutively so that subjects were more immersed in the specifics of each structure. Within each twelve blocks, eight blocks consisted of trials with fixed trajectories (only trials in which one food was unavailable), whilst two blocks consisted of open trajectories (only trials in which both foods were available), and another two consisted of a mix of fixed and open trajectories. The trial order of fixed trajectories was consistent between subjects, and the two open-trajectory blocks enabled us to establish subjects' understanding of the task by checking whether subjects behaved according to the optimal trajectory for each structure.

5.4 Models of progress

In line with our previous suggestions, we adopted an RL approach and formalised progress as a change in value $\delta\mathcal{V}$ between states. In the maze game, each state was assigned a value according to the (negative) number of steps required to reach the goal from that state, with there being only one route to the goal in every maze. This value can be formalised as the optimal value $v_*(s)$, which was computed with a recursive update using value iteration (Eq. 1) until convergence:

$$v_{t+1}(s) = \max_a \sum_{s',r} p(s', r|s, a)[r(s', a) + v_t(s')] \tag{1}$$

where $v_{t+1}(s)$ and $v_t(s')$ are the value of state s at iteration time step $t+1$ and the and value of the next state s' at iteration time step t, respectively, $p(s', r|s, a)$ is the probability of transitioning to state s' with a reward of r given that you are in state s and take action a, and $\max_a$ denotes the maximum value of action a. We used a fully deterministic transition matrix so that participants were in full control of their movement. We set r to a cost of -1 at each state except the goal.

Whilst subjects may not be able to correctly compute this true value during the task, especially in the larger mazes with numerous states, they may estimate their distance to the goal in a similar manner.

We also formalised progress as a change in euclidian distance to assess an alternative account. The value of each state in the maze was computed as the euclidian distance, d, between the state and the goal:

$$d(s,g) = \sqrt{(s_1 - g_1)^2 + (s_2 - g_2)^2} \tag{2}$$

where s_1 is the coordinate of the state along the first dimension, g_1 is the coordinate of the goal along the first dimension, and s_2 and g_2 are the coordinates of the state and goal, respectively, along the second dimension.

In the food service game, we computed the reward structure of each state space according to the underlying geometry of single, additive, multiplicative, and euclidian structures, respectively:

$$\mathcal{R} = x \tag{3}$$

$$\mathcal{R} = x + y \tag{4}$$

$$\mathcal{R} = xy \tag{5}$$

$$\mathcal{R} = \sqrt{x^2 + y^2} \tag{6}$$

where x is the number of pizzas served and y is the number of burgers served. The particular structure of the provision of rewards in the food service game lead to $\mathcal{R}$ acting as a proxy for the value $\mathcal{V}$.

In both games, progress was computed on a trial-by-trial basis. We quantified the absolute progress made during each trial as a change in value between start and end states:

$$\delta\mathcal{V}_t^a = -(\mathcal{V}(s_{t-1}) - \mathcal{V}(s_t)) \tag{7}$$

where $\mathcal{V}(s_t)$ is the value of the current state, or value of the state in which the movement terminated and the pleasure rating was provided, and $\mathcal{V}(s_{t-1})$ is the value of the previous state, or value of the state in which the movement began. Note this value was multiplied by -1 so that positive progress towards the goal is assigned a positive value and vice versa for ease of interpretation.

We then normalised the value change with respect to the maximal value change possible at the start of each trial.

$$\delta\mathcal{V}_t^l = \frac{\mathcal{V}(s_{t-1}) - \mathcal{V}(s_t)}{\mathcal{V}(s_{t-1})} \tag{8}$$

This normalisation allowed us to assess the effect of proximity on progress as the same absolute progress closer to the goal would result in a larger value change under the δV_t^l normalisation.

5.5 Statistical analysis

In all studies, statistical analyses of pleasure ratings were conducted using mixed-effects linear regression modeling in Matlab via the fitlme package. Random effects were included for each subject, with random intercept and slope. Pleasure ratings on each trial were generally modeled as:

$$\mathcal{P}_{it} = \beta_0 + \beta_1\delta\mathcal{V}_{it} + b_{0i} + b_{1i}\delta\mathcal{V}_{it} + \varepsilon_{it} \tag{9}$$

where $\mathcal{P}_{it}$ is pleasure of subject i at time t. Here, β terms denote fixed effects, b terms denote subject-level random effects, and ε_{it} is residual noise.

Due to the misalignment in the scale range for goal progress (-100 to 100) and subjective pleasure ratings (0 to 100) in the self-report study, trials were categorised as either positive or negative progress and modeled separately. Analysis showed no differences in the relationship between goal progress and subjective pleasure ratings between positive and negative progress trials, hence negative progress trials were adjusted by adding 100 to progress ratings and all trials modeled together in subsequent analysis. The scale misalignment was corrected in the replication sample which therefore did not require rating adjustment.

Participants' reported subjective goal distance in self-report studies was also modeled as a function of clinical symptoms $\mathcal{C}_i$ using mixed-effects linear regression modeling, with random intercept only:

$$\mathcal{D}_i = \beta_0 + \beta_1 \mathcal{C}_i + b_{0i} + \varepsilon_i \tag{10}$$

In the maze game and food service game, separate models were fit for progress formalised as $\delta\mathcal{V}_t^a$ and $\delta\mathcal{V}_t^l$ and model fit compared using negative log-likelihood as all models included equal number of parameters.

Data from each of the four mazes in the maze game were first analysed independently, however this revealed no significant differences between mazes hence data were combined for subsequent analysis. The potential interaction between goal progress in and goal importance, specifically the rating of the importance of supporting the charity on each block, was formalised in a mixed-effects linear regression model:

$$\mathcal{P}_{it} = \beta_0 + \beta_1 \delta\mathcal{V}_{it} + \beta_2 \mathcal{I}_{it} + \beta_3 \delta\mathcal{V}_{it}\mathcal{I}_{it} + b_{0i} + b_{1i}\delta\mathcal{V}_{it} + b_{2i}\mathcal{I}_{it} + b_{3i}\delta\mathcal{V}_{it}\mathcal{I}_{it} + \varepsilon_{it} \tag{11}$$

where $\mathcal{I}_{it}$ is the goal importance of subject i at time t.

The effects of altering the belief structure on pleasure experience were assessed with mixed-effects linear regression modeling of data from the food service game. To assess the extent to which progress could be distinctly explained by the relevant underlying structure, progress from each two-dimensional trial was computed in terms of each of the three reward structures. We fit a mixed-effects linear regression model with a joint constant term and separate parameters to represent the progress in each reward structure in terms of each reward structure (Eq. 12), resulting in nine additional parameters:

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_9 \end{bmatrix}, \qquad \mathbf{b}_i = \begin{bmatrix} b_{0i} \\ b_{1i} \\ \vdots \\ b_{9i} \end{bmatrix}, \qquad \mathbf{X}_t = \begin{bmatrix} 1 \\ \delta V_{t,sum}^{sum} \\ \delta V_{t,sum}^{product} \\ \delta V_{t,sum}^{euclid} \\ \delta V_{t,product}^{sum} \\ \delta V_{t,product}^{product} \\ \delta V_{t,product}^{euclid} \\ \delta V_{t,euclid}^{sum} \\ \delta V_{t,euclid}^{product} \\ \delta V_{t,euclid}^{euclid} \end{bmatrix}.$$

$$P_{it} = \mathbf{X}_t^\top \boldsymbol{\beta} + \mathbf{X}_t^\top \mathbf{b}_i \tag{12}$$

where $\delta\mathcal{V}_{t,x}^{y}$ is $\delta\mathcal{V}_t$ for the true structure x modelled as structure y.

In subsequent analysis exploring general relationships between progress and pleasure, data from each reward structure in the food service game were combined and are analysed and reported together. In subsequent analysis exploring the effects of the two-dimensional structure, data from each reward structure are analysed and reported separately.

To assess one-dimensional progress within a two-dimensional structure, we extracted progress trials from the two-dimensional blocks in which the second dimension (i.e. number of burgers served) was zero and progress was made only along the first dimension (i.e. number of pizzas served). Progress on these trials was then recomputed as if they were one-dimensional trials (Eq. 3) and mixed-effects linear regression modeling carried out as before (Eq. 9).

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Data and code availability

Anonymised data, and code for the online tasks and all analyses can be found on GitHub.

References

Ribot, T. *La psychologie des sentiments.* Felix Alcan, Paris. (1896).

Klein, D.F. Endogenomorphic depression. a conceptual and terminological revision. *Archives of General Psychiatry* **31**, 447–454 (1974).

Treadway, M. & Zald, D. Reconsidering anhedonia in depression: Lessons from translational neuroscience (2011).

Trostheim, M., Eikemo, M., Meir, R., Hansen, I., Paul, E. *et al.* Assessment of anhedonia in adults with and without mental illness: A systematic review and meta-analysis. *JAMA Network Open* **3**, e2013233 (2020).

American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders (DSM-5®)*. American Psychiatric Pub (2013).

Gabbay, V., Johnson, A.R., Alonso, C.M., Evans, L.K., Babb, J.S. *et al.* Anhedonia, but not Irritability, Is Associated with Illness Severity Outcomes in Adolescent Major Depression. *Journal of Child and Adolescent Psychopharmacology* **25**, 194–200 (2015).

Spijker, J., Bijl, R.V., De Graaf, R. & Nolen, W.A. Determinants of poor 1-year outcome of DSM-III-R major depression in the general population: Results of the Netherlands Mental Health Survey and Incidence Study (NEMESIS). *Acta Psychiatrica Scandinavica* **103**, 122–130 (2001).

Auerbach, R.P., Pagliaccio, D. & Kirshenbaum, J.S. Anhedonia and Suicide. In D.A. Pizzagalli, ed., *Anhedonia: Preclinical, Translational, and Clinical Integration*, vol. 58 of *Current Topics in Behavioral Neurosciences*, pages 443–464. Springer International Publishing, Cham (2022).

Craske, M.G., Meuret, A.E., Ritz, T., Treanor, M. & Dour, H.J. Treatment for Anhedonia: A Neuroscience Driven Approach. *Depression and Anxiety* **33**, 927–938 (2016).

Parker, G., Hadzi-Pavlovic, D., Wilhelm, K., Hickie, I., Brodaty, H. *et al.* Defining melancholia: properties of a refined sign-based measure. *Br. J. Psychiatry* **164**, 316–26 (1994).

Parker, G. Defining melancholia: the primacy of psychomotor disturbance. *Acta Psychiatr Scand* **115 (Suppl 433)**, 21–30 (2007).

Hall, A.F., Browning, M. & Huys, Q.J.M. The computational structure of consummatory anhedonia. *Trends in Cognitive Science* **28**, 541–553 (2024).

Amsterdam, J.D., Settle, R.G., Doty, R.L., Abelman, E. & Winokur, A. Taste and smell perception in depression. *Biol Psychiatry* **22**, 1481–1485 (1987).

Berlin, I., Givry-Steiner, L., Lecrubier, Y. & Puech, A.J. Measures of anhedonia and hedonic responses to sucrose in depressive and schizophrenic patients in comparison with healthy subjects. *Eur Psychiatry* **13**, 303–309 (1998).

Steiner, J.E., Lidar-Lifschitz, D. & Perl, E. Taste and odor: reactivity in depressive disorders, a multidisciplinary approach. *Perceptual and motor skills* **77**, 1331–1346 (1993).

Dichter, G.S., Smoski, M.J., Kampov-Polevoy, A.B., Gallop, R. & Garbutt, J.C. Unipolar depression does not moderate responses to the sweet taste test. *Depress Anxiety* **27**, 859–863 (2010).

Clepce, M., Gossler, A., Reich, K., Kornhuber, J. & Thuerauf, N. The relation between depression, anhedonia and olfactory hedonic estimates–a pilot study in major depression. *Neurosci Lett* **471**, 139–143 (2010).

Colle, R., El Asmar, K., Verstuyft, C., Lledo, P.M., Lazarini, F. *et al.* The olfactory deficits of depressed patients are restored after remission with venlafaxine treatment. *Psychological Medicine* pages 1–9 (2020).

Kaltenboeck, A., Halahakoon, D.C., Harmer, C.J., Cowen, P. & Browning, M. Enhanced taste recognition following subacute treatment with the dopamine d2/d3 receptor agonist pramipexole in healthy volunteers. *The International Journal of Neuropsychopharmacology* **25**, 720–726 (2022).

Bylsma, L.M., Morris, B.H. & Rottenberg, J. A meta-analysis of emotional reactivity in major depressive disorder. *Clin Psychol Rev* **28**, 676–691 (2008).

Husain, M. & Roiser, J.P. Neuroscience of apathy and anhedonia: a transdiagnostic approach. *Nature reviews. Neuroscience* **19**, 470–484 (2018).

Borsini, A., Wallis, A.S.J., Zunszain, P., Pariante, C.M. & Kempton, M.J. Characterizing anhedonia: A systematic review of neuroimaging across the subtypes of reward processing deficits in depression. *Cognitive, affective behavioral neuroscience* **20**, 816–841 (2020).

Wang, S., Leri, F. & Rizvi, S.J. Anhedonia as a central factor in depression: Neural mechanisms revealed from preclinical to clinical evidence. *Progress in Neuropsychopharmacology & Biological Psychiatry* **110**, 110289 (2021).

Huys, Q.J., Pizzagalli, D.A., Bogdan, R. & Dayan, P. Mapping anhedonia onto reinforcement learning: A behavioural meta-analysis. *Biology of Mood & Anxiety Disorders* **3**, 12 (2013).

Gard, D., Gard, M., Kring, A. & John, O. Anticipatory and consummatory components of the experience of pleasure: a scale development study. *J Res Personality* **40**, 1086–1102 (2006).

Dayan, P. & Berridge, K.C. Model-based and model-free pavlovian reward learning: revaluation, revision, and revelation. *Cogn Affect Behav Neurosci* **14**, 473–492 (2014).

Dayan, P. ”liking” as an early and editable draft of long-run affective value. *PLoS Biology* **20**, e3001476 (2022).

Treadway, M.T., Bossaller, N.A., Shelton, R.C. & Zald, D.H. Effort-based decision-making in major depressive disorder: a translational model of motivational anhedonia. *J Abnorm Psychol* **121**, 553–558 (2012).

Cooper, J.A., Arulpragasam, A.R. & Treadway, M.T. Anhedonia in depression: biological mechanisms and computational models. *Current opinion in behavioral sciences* **22**, 128–135 (2018).

Wang, S., Leri, F. & Rizvi, S.J. Clinical and preclinical assessments of anhedonia in psychiatric disorders. *Current topics in behavioral neurosciences* **58**, 3–21 (2022).

Lally, N., Nugent, A.C., Luckenbaugh, D.A., Ameli, R., Roiser, J.P. *et al.* Anti-anhedonic effect of ketamine and its neural correlates in treatment-resistant bipolar depression. *Translational psychiatry* **4**, e469 (2014).

Lally, N., Nugent, A.C., Luckenbaugh, D.A., Niciu, M.J., Roiser, J.P. *et al.* Neural correlates of change in major depressive disorder anhedonia following open-label ketamine. *Journal of Psychopharmacology (Oxford, England)* **29**, 596–607 (2015).

Singh, S., Lewis, R.L. & Barto, A.G. Where do rewards come from? In *Proceedings of the annual conference of the Cognitive Science Society*, pages 2601–2606. Cognitive Science Society (2009).

Dawkins, R. *The Genetic Boook of the Dead: A Darwinian Reverie*. Apollo (2024).

Ashar, Y.K., Gordon, A., Schubiner, H., Uipi, C., Knight, K. *et al.* Effect of pain reprocessing therapy vs placebo and usual care for patients with chronic back pain: A randomized clinical trial. *JAMA psychiatry* **79**, 13–23 (2022).

Yeager, D.S., Bryan, C.J., Gross, J.J., Murray, J.S., Krettek Cobb, D. *et al.* A synergistic mindsets intervention protects adolescents from stress. *Nature* **607**, 512–520 (2022).

Keramati, M. & Gutkin, B.S. A reinforcement learning theory for homeostatic regulation. In J. Shawe-Taylor, R. Zemel, P. Bartlett, F. Pereira & K. Weinberger, eds., *Advances in Neural Information Processing Systems 24*, pages 82–90. Curran Associates, Inc. (2011).

Heath, C., Larrick, R.P., & Wu, G. Goals as reference points. *Cognitive Psychology* **38**, 79–109 (1999).

Kivetz, R., Urminsky, O. & Zheng, Y. The goal-gradient hypothesis resurrected: Purchase acceleration, illusionary goal progress, and customer retention. *Journal of marketing research* **43**, 39–58 (2006).

Cortese, A., Yamamoto, A., Hashemzadeh, M., Sepulveda, P., Kawato, M. *et al.* Value signals guide abstraction during learning. *eLife* **10** (2021).

Rutledge, R.B., Skandali, N., Dayan, P. & Dolan, R.J. A computational and neural model of momentary subjective well-being. *Proceedings of the National Academy of Sciences* **111**, 12252–12257 (2014).

Eldar, E., Rutledge, R.B., Dolan, R.J. & Niv, Y. Mood as representation of momentum. *Trends in Cognitive Sciences* **20**, 15–24 (2016).

Bennett, D., Davidson, G. & Niv, Y. A model of mood as integrated advantage. *Psychological review* **129**, 513–541 (2022).

Keren, H., Zheng, C., Jangraw, D., Chang, K., Vitale, A. *et al.* The temporal representation of experience in subjective mood. *ELife* **10**, e62051 (2021).

Ng, A.Y., Harada, D. & Russell, S. Policy invariance under reward transformations: Theory and application to reward shaping. *ICML* **99**, 278–287 (1999).

Keramati, M. & Gutkin, B. Homeostatic reinforcement learning for integrating reward collection and physiological stability. *eLife* **3**, e04811 (2014).

Lieder, F., Chen, O.X., Krueger, P.M. & Griffiths, T.L. Cognitive prostheses for goal achievement. *Nature Human Behaviour* **3**, 1096–1106 (2019).

Berridge, K.C. & Robinson, T.E. Parsing reward. *Trends Neurosci* **26**, 507–513 (2003).

Sclafani, A. Post-ingestive positive controls of ingestive behavior. *Appetite* **36**, 79–83 (2001).

Sclafani, A. Gut–brain nutrient signaling. appetition vs. satiation. *Appetite* **71**, 454–458 (2013).

De Araujo, I.E., Oliveira-Maia, A.J., Sotnikova, T.D., Gainetdinov, R.R., Caron, M.G. *et al.* Food reward in the absence of taste receptor signaling. *Neuron* **57**, 930–941 (2008).

Berridge, K.C. & Robinson, T.E. Liking, wanting, and the incentive-sensitization theory of addiction. *American Psychologist* **71**, 670 (2016).

Morales, I. & Berridge, K.C. 'liking'and 'wanting'in eating and food reward: Brain mechanisms and clinical implications. *Physiology behaviour* **227**, 113152 (2020).

Ryali, C.K., Goffin, S., Winkielman, P. & Yu, A.J. The role of statistical typicality in human social assessment of faces. *Proceedings of the National Academy of Sciences* **117**, 29371–29380 (2020).

Brielmann, A.A., Berentelg, M. & Dayan, P. Modelling individual aesthetic judgements over time. *Philosophical Transactions of the Royal Society B* **379**, 20220414 (2024).

Colle, R., Asmar, K.E., Verstuyft, C., Lledo, P.M., Lazarini, F. *et al.* The olfactory deficits of depressed patients are restored after remission with venlafaxine treatment. *Psychological Medicine* **52**, 2062–2070 (2022).

Atanasova, B., El-Hage, W., Chabanet, C., Gaillard, P., Belzung, C. *et al.* Olfactory anhedonia and negative olfactory alliesthesia in depressed patients. *Psychiatry Research* **176**, 190–196 (2010).

Kohli, P., Soler, Z.M., Nguyen, S.A., Muus, J.S. & Schlosser, R.J. The Association Between Olfaction and Depression: A Systematic Review. *Chemical Senses* **41**, 479–486 (2016).

Berenbaum, H. & Connelly, J. The effect of stress on hedonic capacity. *Journal of Abnormal Psychology* **102**, 474–481 (1993).

Bogdan, R. & Pizzagalli, D.A. Acute stress reduces reward responsiveness: implications for depression. *Biol Psychiatry* **60**, 1147–1154 (2006).

Min, S., Mazurka, R., Pizzagalli, D.A., Whitton, A.E., Milev, R.V. *et al.* Stressful life events and reward processing in adults: Moderation by depression and anhedonia. *Depression and Anxiety* **2024**, 8853631 (2024).

Phillips, R., Walsh, E., Jensen, T., Nagy, G., Kinard, J. *et al.* Longitudinal associations between perceived stress and anhedonia during psychotherapy. *Journal of Affective Disorders* **330**, 206–213 (2023).

Jacobson, N.S., Dobson, K.S., Truax, P.A., Addis, M.E., Koerner, K. *et al.* A component analysis of cognitive-behavioral treatment for depression. *J Consult Clin Psychol* **64**, 295–304 (1996).

Martell, C.R., Dimidjian, S. & Herman-Dunn, R. *Behavioral Activation for Depression*. The Guilford Press, New York, USA (2010).

Craske, M.G., Meuret, A.E. & Echiverri-Cohen, A. Positive Affect Treatment Targets Reward Sensitivity: A Randomized Controlled Trial. *Journal of Consulting and Clinical Psychology* **91**, 350–366 (2023).

Dunn, B.D., Widnall, E., Warbrick, L., Warner, F., Reed, N. *et al.* Preliminary clinical and cost effectiveness of augmented depression therapy versus cognitive behavioural therapy for the treatment of anhedonic depression (adept): a single-centre, open-label, parallel-group, pilot, randomised, controlled trial. *EClinical Medicine* **61** (2023).

Cernasov, P., Walsh, E.C., Kinard, J.L., Kelley, L., Phillips, R. *et al.* Multilevel growth curve analyses of behavioral activation for anhedonia (BATA) and mindfulness-based cognitive therapy effects on anhedonia and resting-state functional connectivity: Interim results of a randomized trial. *Journal of Affective Disorders* **292**, 161–171 (2021).

Garland, E.L., Fix, S.T., Hudak, J.P., Bernat, E.M., Nakamura, Y. *et al.* Mindfulness-Oriented Recovery Enhancement remediates anhedonia in chronic opioid use by enhancing neurophysiological responses during savoring of natural rewards. *Psychological Medicine* **53**, 2085–2094 (2021).

Carlton, C.N., Antezana, L., Garcia, K.M., Sullivan-Toole, H. & Richey, J.A. Mindfulness-Based Stress Reduction Specifically Improves Social Anhedonia Among Adults with Chronic Stress. *Affective Science* **3**, 145–159 (2022).

Marin, R.S., Biedrzycki, R.C. & Firinciogullari, S. Reliability and validity of the apathy evaluation scale. *Psychiatry Research* **38**, 143–162 (1991).

Zung, W.W.K. A self-rating depression scale. *Archives of general psychiatry* **12**, 63–70 (1965).

Khazanov, G.K., Ruscio, A.M. & Forbes, C.N. The positive valence systems scale: Development and validation. *Assessment* **10**, 1045–1069 (2020).

Insel, T.R. The nimh research domain criteria (rdoc) project: Precision medicine for psychiatry. *American Journal of Psychiatry* **171**, 395–397 (2014).

Löwe, B., Kroenke, K., Herzog, W. & Gräfe, K. Measuring depression outcome with a brief self-report instrument: sensitivity to change of the patient health questionnaire (phq-9). *Journal of affective disorders* **81**, 61–66 (2004).

Beck, A., Weissman, A., Lester, D. & Trexler, L. The measurement of pessimism: The hopelessness scale. *J Consult Clin Psychol* **42**, 861–865 (1974).