Two-dimensional Reward Evaluation and Its Relevance to Anhedonia

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Abstract:

Many real-life decisions involve balancing multiple needs at the same time. To capture such complexity, We can conceptualize reward processing as navigating in an abstract value space. To tap into the individual differences in 'value navigation', we designed a foraging task where participants pick fruits to satisfy one of two needs, hydration and energy. The points they earn map onto how close they are to the goal state in Euclidean distance. In three studies (N = 685), we found that people systematically preferred the reward options that satisfied a single need (unidimensional bias), even when the option that satisfies both needs rendered higher points. Surprisingly, participants who reported a reduced capacity to imagine future pleasure (anticipatory anhedonia) had a smaller unidimensional bias, and therefore had better task performance. This may suggest that participants with anticipatory anhedonia represented values more veridically in a task that requires value representation in Euclidean geometry.

Keywords: reward processing; anhedonia; motivation

In real life, reward processing usually involves balancing different needs by varying reward choices. Juechems and Summerfield (2019) proposed a geometric formulation for value representation, where an agent aims to minimize their distance from a goal state in multidimensional value space. Importantly, this reward geometry may be different across people (Huys & Browning, 2021).

Anhedonia, the inability to experience pleasure, is a transdiagnostic symptom in mental illnesses. It includes anticipatory anhedonia (anticipating future pleasure) and consummatory anhedonia (responding to present reward stimuli) (Berridge & Robinson, 1998). Self-reported anhedonia has been linked to increased random exploration and decreased reward sensitivity in reinforcement learning tasks (Huys et al., 2013). In this study, we asked whether individual differences in this geometric representation of value is related to self-reported anhedonia in community population. Moreover, we asked which aspect of anhedonia, anticipatory or consummatory, is relevant.

Methods

We recruited online participants (N = 140, 169 and 376 in three studies) to play a foraging game (Fig 1A). Participants choose from one of three fruits that differentially supplement their two needs, hydration and energy, shown on the screen as progress bars. Their goal was to earn as many health points as possible by maintaining both needs within an optimal range (not too low and not too high). At the beginning of each "day", participants started with certain levels of hydration and energy. Importantly, the health points that participants received in each trial was inversely proportional to their Euclidean distance to the goal (Fig 1B). Thus, there is an optimal choice at every location on the value map. Participants picked 5 fruits sequentially on each "day", and health points and the change in two needs were revealed after each choice. Each game included 27-30 blocks, depending on its version. Anhedonia was measured using the Temporal Experience of Pleasure Scale (Gard et al., 2006).

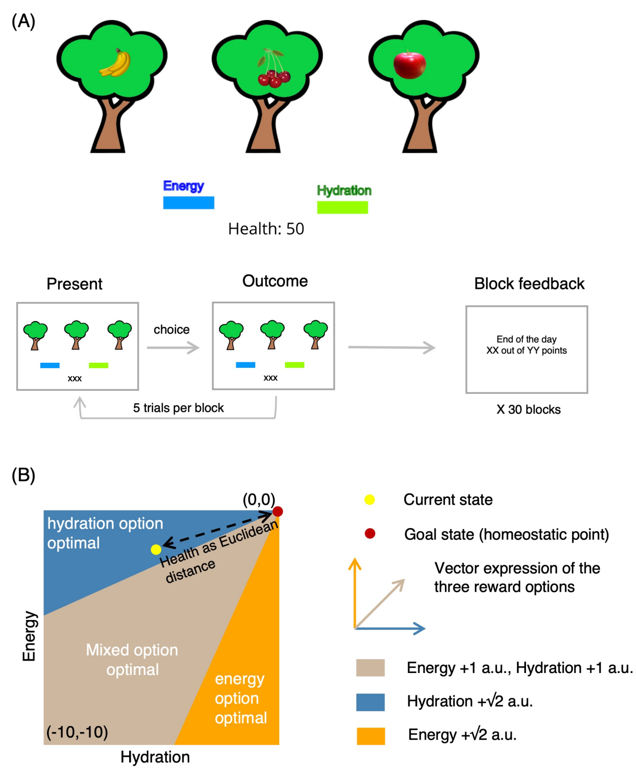

Figure 1: (A) The two-dimensional value-based decision-making task. (B) The underlying Euclidean value map.

We modeled individual choices as drawn from a stable geometric representation of values. The reward value of a chosen option $\boldsymbol{r} = (\Delta h, \Delta e)$ at the current state (h_1, e_1) was calculated as the distance moved towards the goal and was influence by two parameters p and q which controlled the geometry of the value space ($p = q = 2$ corresponds to a Euclidean space, and $p = q = 1$ a Manhattan space):

$$Q_{h,e,r} = \sqrt[q]{(h_1 + \Delta h)^p + (e_1 + \Delta e)^p} - \sqrt[q]{{h_1}^p + {e_1}^p}$$

The probability of choosing one of three certain reward options was determined using a SoftMax function with an inverse temperature parameter β quantifying the randomness of behavior given the same value representation.

Setting q = 2, we estimated the expected p and β values for each participant. Only trials within the upper bound (energy and hydration < -1.4 a.u. in Fig 1B) were used, because the model predicts loss aversion at the borders. Study 1 was not modelled because of a high exclusion rate at the borders.

Results

People prefer unidimensional reward options

Compared to the optimal strategy, people were biased away from choosing the mixed option that increases both hydration and energy (study 1: $t_{(1,139)}$ = 10.61, Cohen's d = 0.90; study 2: $t_{(1,168)}$ = 15.82, Cohen's d = 1.22; study 3: $t_{(1,375)}$ = 25.89, Cohen's d = 1.34; all p < 10^{-5}), despite the fact that choosing the mixed reward option was linearly associated with higher health points (study 1: β = 0.80, η^2 = 0.63; study 2: β = 0.92, η^2 = 0.86; study 3: β = 0.92, η^2 = 0.85; all p < 10^{-5}).

Anticipatory anhedonia is associated with diminished unidimensional bias

In all three studies, participants with lower TEPS-ANT score, indicative of higher anticipatory anhedonia, chose the mixed option more often (Poisson regression, study 1: B = -0.16, z = -7.10, study 2: B = -0.013, z = -8.52; study 3: B = -0.07, z = -8.36; all p < 10^{-5}) and thus earned more health points. To understand *where* in the value map participants with higher anticipatory anhedonia outperformed other participants, we fitted a logistic regression model to trial-by-trial choices as a function of need levels and TEPS-ANT. Participants with higher anticipatory anhedonia not only choose more mixed option in general, but also choose the mixed option more when hydration and energy levels were both low or both high (Fig 2; three way interactions, study 1: B = -0.0009, z = -5.09, p < .001; study 2: B = -0.0025, z = -13.54, p < .001; study 3: B = -0.0045, z = -2.33, p = .020).

Value representation accounts for individual differences in task performance

Participants with higher TEPS-ANT had a p value closer to 1, suggestive of a Manhattan-like geometric representation (Poisson regression; study 2: B = -0.045, z = -3.23, p = .001; study 3: B = -0.02, z = -2.58, p = .01). Differences in parameter p fully mediated the link between anticipatory anhedonia and task performance, after controlling for β (study 3: mediated effect = -0.62, p = .004, direct effect = -0.28, p = .39; study 3: mediated effect = -0.24, p = .03, direct effect = -0.03, p = .66).

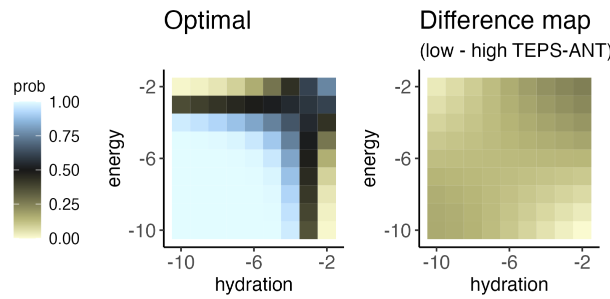

Figure 2: Probability of mixed reward option as a function of location on the value map. Left: optimal scenario from task geometry; Right: difference in probability between participants with high versus low anticipatory anhedonia.

Conclusion

In a foraging task that encourages a Euclidean representation of value, human participants formed a more Manhattan-like representation, assigning greater values to unidimensional options. Surprisingly, participants who reported higher anticipatory anhedonia performed better in this task, and appeared to solve the task using a more veridical representation of reward geometry.

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