Anhedonia and Depression in Youth: Real-World and Computational Evidence of Impaired Reward Processing

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कर्मण्येवाधिकारस्ते मा फलेषु कदाचन ।

मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि ॥४७॥

You have a right to perform your prescribed duties, but you are not entitled to the fruits of your actions।

Never consider yourself to be the cause of the results of your activities, nor be attached to inaction॥47॥

- Bhagavad Gītā, Chapter 2, Verse 47

Declaration

I can confirm that this is my own work and that the use of all materials from other sources has been properly and fully acknowledged.

Angad Sahni

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Abstract

Background: Major Depressive Disorder (MDD) is the leading cause of disability in young people, and predicts increased risk of suicide and unemployment in adulthood. Anhedonia, the loss of interest and pleasure, is a core symptom of depression. Impairments in reward processing sub-components (anticipation, motivation, consummatory and learning) are thought to underlie anhedonia symptoms. Discovering novel reward-based treatment targets in young people could protect against poor outcomes in adulthood.

Ecological momentary assessment (EMA) questionnaires examine reward processing in real-life, removing recall biases. Previous EMA studies have demonstrated deficits in anticipatory and consummatory pleasure in depression vs controls. Studies have also reported lower mood in depressed individuals, i.e. lower positive affect (PA) and elevated negative affect (NA). The Mood brightening (MB) effect has been observed, where positively-rated events lead to greater increases in PA and greater reductions in NA in depression vs controls. Lab-based experimental tasks demonstrate depressed individuals less frequently choose to exert effort for rewards, suggesting deficits in motivation. Probabilistic learning tasks show individuals failing to develop response biases to more rewarding choices, suggesting reduced exposure to rewarding experiences in depression.

Leisure activities and social company are known to protect against depression, but inactivity and social isolation are more prevalent. Understanding how to increase compliance with rewarding activities would improve outcomes in depressed youth. However, how to increase enjoyment and engagement in pleasurable activities remains unclear, and the MB effect of such activities remains scarcely examined. Lastly, experimental tasks have rarely combined learning to maximize rewards with exerting effort to attain them, which closely capture the real-life dynamics of reward processing.

Methods: Young people (16-25 yrs old) were recruited from local schools and the university. Depression symptoms were measured using the Mood and Feelings Questionnaire (MFQ) and the Beck Depression Inventory-II (BDI). Anhedonia symptoms were measured using the Temporal Experience of Pleasure Scale (TEPS), the Snaith-Hamilton Pleasure Scale (SHAPS), and the Anhedonia Scale for Adolescents (ASA).

The EMA protocol adapted from Edwards et al. (2018), presenting seven daily assessments for 6 days on smartphones. Participants selected from multiple choices for physical activities and company, then rated anticipation (anticipatory pleasure, expectation) and motivation (preference, interest) for planned activities, enjoyment of current activity, and mood (PA, NA) on 7-point Likert scales. The physical activities were categorised as Leisure (relaxing, exercising, other leisure activities) or Functional (work/school, hygiene, etc.), and company as Social (friends, family, partner) or Non-Social (alone).

In Paper 1, participants (N=80; 2,316 assessments) were classified by depression severity: high (HD, MFQ ≥ 27, n=42), moderate (MD, MFQ 16–27, n=16), and controls (C, MFQ ≤ 16, n=22). Multilevel models examined time-lagged relationships: how anticipation and motivation (t-1) predict the enjoyment and engagement in Leisure activities and Social company (t). Linear regressions examined how depression symptoms predict time spent in activities. Paper 2 used EMA mood data from participants (N=71; 2,177 assessments). Affective reactivity was measured as change from two baselines: mean affect and affect (t-1). Multilevel models examined how depression and anhedonia symptoms (MFQ, ASA) predicted reactivity, and how context (Leisure, Social) moderated this relationship.

For Paper 3, an online reward and effort learning task was adapted from Frey et al. (2023). Participants (N=155) chose between two shapes, each requiring effort exertion (high/low button presses) to acquire rewards (puppy/dog image). Reward and effort learning blocks, 25 trials each, required participants to maximize reward or minimize effort, respectively. Outcome contingencies were 25/75%. Q-learning equations modelled choice data with parameters (learning rate, explore/exploit parameter) capturing aspects of learning. Correlations examined relationships of anhedonia (SHAPS, TEPS) with subjective ratings of rewards (liking, wanting, effort willingness), task performance, and parameter values. Corrected for multiple comparisons.

Results: Paper 1 revealed young people with higher depression symptoms spent less time on work/school and hygiene. When planned (t-1) and actual activities (t) matched, higher anticipatory pleasure predicted greater engagement and more enjoyment from leisure activities and social company in HD group (Paper 1). Paper 2 revealed that engaging in leisure activities or social company predicted greater decreases in NA at higher depression symptoms, but not PA.

As expected, Paper 3 revealed lower liking, wanting and effort willingness for puppy images with increasing anhedonia. Further, lower effort and reward learning accuracies correlated with increasing consummatory anhedonia. Computational modelling revealed that higher temperature values may underlie this, suggesting over-exploration of less rewarding options.

Limitations: As the sample consisted mostly of highly-educated females, generalizability of these findings is limited. Seven questionnaires per day restrict the number of time-lagged relationships that can be captured. Preference for puppy and dog images may vary, which may influence results.

Conclusions: Episodic future thinking (EFT) is shown to enhance anticipatory pleasure. Future studies should examine if EFT increases enjoyment and engagement in leisure activities and social company in depression. These activities are likely to elevate mood by reducing NA at higher depression symptoms, so managing negative emotions could be encouraged in depressed individuals. Exploring how social rewards are processed using the reward and effort learning task and EMA is encouraged, as these are more salient for young people. Studies are novel - a strength but few previous studies to evaluate findings against. Replication of all studies in larger samples is suggested.

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1. General Introduction

This section has been adapted from a literature review invited by Nature Reviews: Psychology (Ma et al., 2024). For this thesis, the sections on Ecological Momentary Assessments (**1.4.3.**) and Computational Modelling (**1.4.2.***iii.*) were expanded.

1.1. Depression in Adolescents

Major Depressive Disorder (MDD) is amongst the leading causes of disability in adolescents (Vos et al., 2020; WHO, 2014), and is projected to be the biggest burden of disease by 2030 (Malhi & Mann, 2018). Depression in adolescents is associated with impaired social functioning, poor familial relationships, increased use of mental health services and risk of suicide (Carrellas et al., 2017). Youth depression predicts a reduced likelihood of getting married, of having a higher household incomes and of having children in adulthood (Chang & Kuhlman, 2022). Such poor concurrent and future outcomes of adolescent-onset depression stress the need for developing effective treatments.

1.2. Current Treatments and Poor Outcomes

Meta-analyses have shown that psychotherapies are only moderately better than care-as-usual and waiting list conditions at reducing depression symptoms, regardless of the format of interventions (Cuijpers et al., 2021; Eckshtain et al., 2020; Weisz et al., 2006). The repair of depression symptoms by psychotherapeutic interventions, such as behavioural activation (BA) and cognitive behavioural therapy (CBT), is shown to be impaired at higher anhedonia symptoms in a large randomised controlled trial (RCT) (Alsayednasser et al., 2022). Further, anhedonia is found to correlate with poorer response to antidepressants in MDD adults (Khazanov et al., 2020; Luca et al., 2024; Vinckier et al., 2017; Vitiello & Ordóñez, 2016) and youth (McMakin et al., 2012). It is also shown to predict a greater likelihood of relapse after remission, and a longer time to remission in treatment-resistant youth (McMakin et al., 2012) and adults (Khazanov et al., 2020).

Anhedonia, a diminished experience of interest and pleasure, has been characterised as a dysfunction in reward processing and a core diagnostic symptom of MDD (American Psychiatric Association, 2013). Higher anhedonia symptoms are also associated with deficits in physical and social functioning (S. Wong et al., 2024), quality of life (Burger et al., 2016; IsHak et al., 2015) and productivity in depression (Beck et al., 2011). These psychosocial deficits are even shown to persist despite a reduction in depression symptoms with antidepressants (Vinckier et al., 2017).

Together, these findings suggest that directly targeting anhedonia symptoms may improve efficacy of pharmaco- and psycho-therapeutic interventions, with further evidence suggesting that reducing anhedonia symptoms can also improve treatment initiation and prolong compliance (Khazanov et al., 2022). A systematic review, evaluating the efficacy of all types of antidepressants (melatonergic, selective serotonin reuptake inhibitors, tricyclic, etc.) on reducing anhedonia symptoms in MDD, has demonstrated a lack of pronounced improvements (Cao et al., 2019). Therefore, there is a real need to develop interventions to effectively alleviate anhedonia symptoms in depressed individuals, to improve the efficacy of current treatments and daily life functioning.

Given that many mental illnesses first appear before the age of 24 (Blakemore, 2019) and adolescent-onset depression predicts poor future outcomes (Carrellas et al., 2017; Chang & Kuhlman, 2022), this thesis will focus on examining the impairments in reward processing associated with anhedonia and depression symptoms in young people, ages 16 to 25 years old. Utilising the pervasive use of smartphones amongst young people today, this thesis will attempt to synthesise digital interventions from its original research.

1.3. Reward Processing Sub-Components

The earliest definition of anhedonia is by Ribot (1896) as the “inability to experience pleasure” from rewards, and was understood to be a unitary construct. However, research into how rewards are processed have revealed that reward processing is instead made up of the following temporally distinct, cyclically-linked sub-components: “wanting” (the desire to acquire a reward that corresponds with appropriate action), “liking” (once acquired, reward is consumed and enjoyed) and “learning” (remembering the enjoyment of the reward that informs the future experience of “wanting”) (Berridge & Kringelbach, 2008, 2013; Robinson & Berridge, 1993). These are sometimes described as mapping on to the appetitive, consummatory and satiety phases, respectively, of the pleasure cycle (Kringelbach et al., 2012). Treadway and Zald (2011), Kring and Barch (2014) and Thomsen (2015) further elaborated that the appetitive phase includes a decision making component, whereby the computation of the value of reward and the effort required to acquire it is calculated. This leads to *approach motivation* and goal-directed behaviour (or *effort exertion*). The pleasure sub-components of reward processing have been distinguished between *anticipatory pleasure* (the pleasure experienced when looking forward to a future reward) and *consummatory pleasure* (the in-the-moment enjoyment of an acquired reward) (Kring & Barch, 2014; Thomsen, 2015). *Expectation* (likelihood of acquiring a reward) is characterised as the cognitive aspect of *anticipation* (Edwards et al., 2018), representing reward prediction errors according to Kring and Barch (2014), and *anticipatory pleasure* is its affective component. Lastly, the learning sub-component has been conceptualized as *updating* and *activating reward-related pleasure* (the pleasure associated with a reward is *updated* based on previous experiences and is *activated* to address the anticipatory pleasure) (Figure 1).

As anhedonia is known to reflect dysfunctions in reward processing (Ely et al., 2021), this thesis will further evaluate the evidence of how anhedonia and depression symptoms are associated with dysfunctions in each sub-component, identify the gaps in knowledge, and address them in original research.

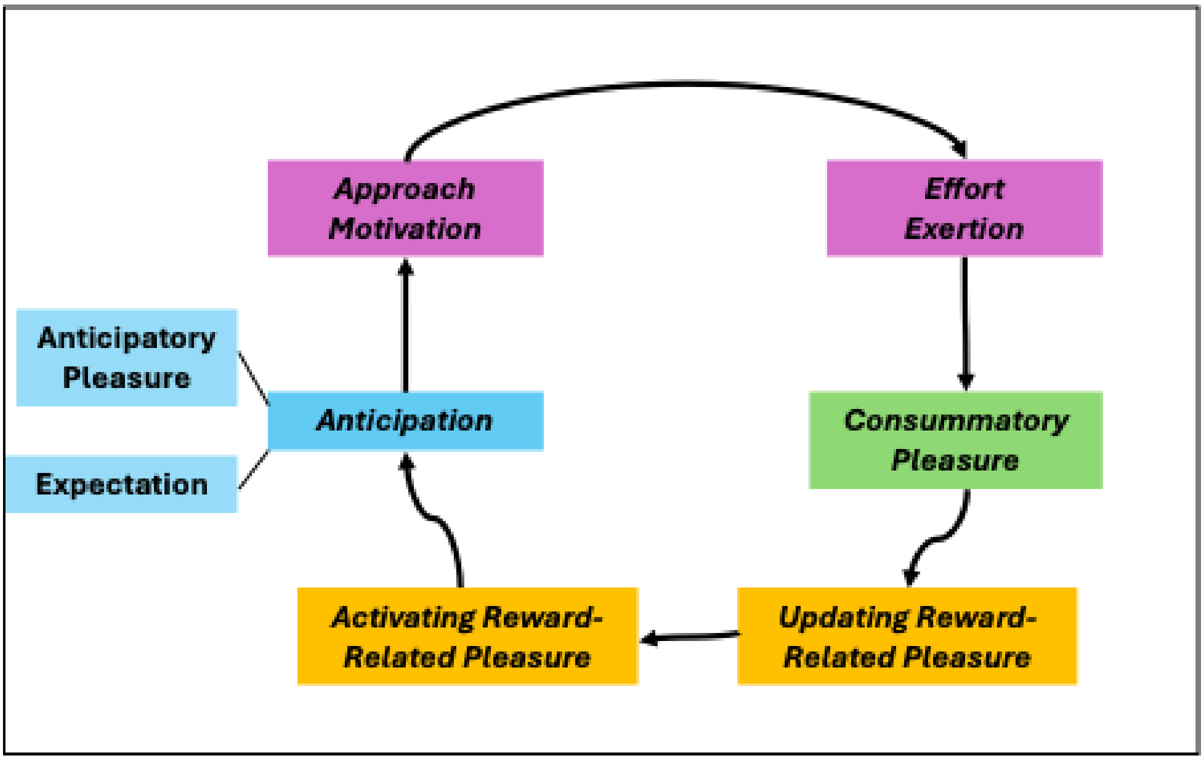

Figure 1: The temporal experience of pleasure (TEP) cycle, adapted* from Kring and Barch (2014).

The colours represent the constructs of each sub-component of reward processing: Anticipation (blue), Motivation/Effort (purple), Consummatory (green) and Learning (orange).

*The adaptation from King and Barch (2014) included specifying the 'feeling' and 'prediction' aspects of Anticipation as Anticipatory Pleasure and Expectation, respectively.

1.4. Understanding the Mechanisms of Anhedonia

In this section, each sub-component of reward will be discussed in relation to depression and anhedonia symptoms, and the behaviour-related methodologies that were used to identify it and their limitations. This will help us identify the new developments in studying each sub-component's functioning and utilise them in our original research. To this end, the two methodologies that have been commonly used to assess reward processing - self-report questionnaires and experimental tasks - will be reviewed alongside a third newer methodology that is being applied to examine real-world reward processing, Ecological Sampling Methodology (ESM; Shiffman et al., 2008) (also known as ecological momentary Assessments (EMA)). Typically, self-reported questionnaires measure the subjective symptom of anhedonia, while experimental tasks assess the objective processing of rewards and effort costs (McCabe, 2018). To gain a deeper mechanistic understanding of anhedonia, the next few subsections will review what each methodology reveals about the impairments in each reward processing sub-component (Figure 1), which has been recommended previously (Pizzagalli, 2022). This has also been captured by the Research Domain Criteria (RDoC) initiative from the National Institute of Mental Health (https://www.nimh.nih.gov/research/research-funded-by-nimh/rdoc/constructs/positive-valence-systems), which states that the positive valence system (PVS) is responsible for reward-related behaviours, such as reward learning, motivation and consummatory behaviour – as captured by the TEPS cycle (Figure 1).

1.4.1. Self-Report Questionnaires

Several questionnaires used to measure depression severities, such as the Beck Depression Inventory-II (BDI-II; Beck et al., 1996), the Montgomery-Asberg Depression Rating Scale (MADRS; Montgomery & Åsberg, 1979), the Mood and Feelings Questionnaire (MFQ; Angold & Costello, 1987) and the Hamilton Depression Rating Scale (HAM-D; Hamilton, 1960), do not include anhedonia as a major construct. For example, only 4 items in the BDI-II (Pizzagalli et al., 2005) describe the anhedonia symptom, which capture only a general deficit in the experience of positive emotion and include measures of the loss of interest in work and sex, which could be considered less relevant to the lives of adolescents and young people (Kaya & McCabe, 2019; McCabe, 2018). Further, given only a few items in depression questionnaires measure anhedonia, the reward processing sub-components that could contribute to the symptom cannot be fully examined.

i. Unitary Construct

Validated self-report measures of anhedonia used in clinical research include the Snaith-Hamilton Pleasure Scale (SHAPS; Snaith et al., 1995), the Fawcett-Clark Pleasure capacity Scale (FCPS; Fawcett, 1983), and the Chapman Physical Anhedonia Scale (CPAS) and Chapman Social

Anhedonia Scale (CSAS) (Chapman et al., 1976). While CPAS and CSAS measure motivational, effort and consummatory pleasure aspects of anhedonia, they were developed for use in schizophrenia and so associate strongly with non-affective symptoms of psychotic disorders, such as hallucinations, delusions, and disorganised thinking (Leventhal et al., 2006). Anhedonia measured by CPAS and CSAS is, therefore, speculated to be a consequence of such psychiatric disturbances (Bailey et al., 1993; Katsanis et al., 1990; Schuck et al., 1984).

The FCPS and SHAPS measure only the unitary construct of hedonic capacity, but both were specifically developed in MDD (Leventhal et al., 2006; Nakonezny et al., 2010). The SHAPS has been validated in a non-depressed adolescent population (Leventhal et al., 2015) and in adult outpatients with MDD (Nakonezny et al., 2015). As such, the SHAPS is recommended as the gold standard for anhedonia measurement in depression, in part because its items measure consummatory pleasure across various domains in real life, such as favourite food/drink and hobbies (Rizvi et al., 2016).

Taken together with a meta-analysis showing significantly higher SHAPS in MDD compared to healthy controls (HCs), and even schizophrenia and bipolar disorder, it provides strong evidence of deficits in the experience of enjoyment of real-life rewarding activities in depression (Trøstheim et al., 2020). Furthermore, though many of the studies were in adults, there were several that were focused on or included adolescents (for example: Cullen et al., 2018; Lawson et al., 2017; Liu, Wang, Zhao, et al., 2012; Liu, Wang, Zhu, et al., 2012; Osuch et al., 2016; Pechtel et al., 2013; Pechtel & Pizzagalli, 2013; Young et al., 2014), suggesting that deficits in enjoyment of rewards may comprise a mechanism of anhedonia in adolescent depression.

ii. Multiple Constructs

Questionnaires that capture multiple sub-components of anhedonia include the Mood and Anxiety Symptom Questionnaire (MASQ; Watson et al., 1995), containing the anhedonic depression scale that has one motivation item ("took effort to get started") but mostly anticipatory pleasure aspects. This measure of anhedonia may, however, be confounded by items that appear to be distant and downstream consequences of prolonged exposure to depressive symptoms and other factors.

These include items such as suicidal thoughts ("thought about death or suicide") and speed of movement ("felt slowed down"), as suicidal ideation is strongly predicted by stressful life events (Li et al., 2022) and psychomotor retardation is observed in MDD (reviewed here: Buyukdura et al., 2011).

More recent developments include the Temporal Experience of Pleasure Scale (TEPS; Gard et al., 2006), the Motivation and Pleasure Scale Self-Report (MAP-SR; Llerena et al., 2013), the Anticipatory and Consummatory Interpersonal Pleasure Scale (ACIPS; Gooding & Pflum, 2014a, 2014b), the Specific Loss of Interest Scale (SLIPS; Winer et al., 2014), and the Dimensional Anhedonia Rating Scale (DARS; Rizvi et al., 2015).

MAP-SR has been validated in schizophrenia patients (Llerena et al., 2013), but its motivation-related items focus only on work and school, which may not fully capture the experience of adolescents. However, this scale did identify the distinction between pleasure and motivation sub-components. This distinction is also seen in brain regions, as confirmed by a meta-analysis of neuroimaging studies, demonstrating that motivation-related impairments in MDD are localised to frontal areas (orbitofrontal cortex) but pleasure-related impairments are frontostriatal (caudate, anterior cingulate cortex) (Borsini et al., 2020).

Though items in ACIPS and SLIPS capture anticipatory and consummatory pleasure aspects of social anhedonia, factor analyses showed no clear distinction (Gooding & Pflum, 2014a, 2014b; Winer et al., 2014) making it difficult to know if these measures can truly map onto reward sub-component processes. The TEPS also attempts to distinguish between anticipatory (TEPS-A) and consummatory (TEPS-C) aspects of physical anhedonia (Gard et al., 2006), but some report that they are highly correlated and do not easily dissociate (Garfield et al., 2016; Ho et al., 2015). As greater sensitivity to social reward is observed in adolescence (Foulkes & Blakemore, 2016), it could be argued that self-report questionnaires should also measure social anhedonia symptoms and not just physical symptoms.

Regardless, the TEPS provides interesting insight into the possible mechanisms of anhedonia, where deficits in both anticipatory and consummatory pleasure are observed in MDD adults (Liu, Wang, Zhao, et al., 2012; Liu et al., 2021; Yang et al., 2017) and in adolescents with a high risk of depression (Rzepa et al., 2017; Rzepa & McCabe, 2016). However, deficits in both sub-components (Li et al., 2015), no difference (Wang et al., 2015), and, overwhelmingly, deficits in anticipatory but not consummatory pleasure (Chan et al., 2010; Favrod et al., 2009; Fortunati et al., 2015; Gard et al., 2007; Mote et al., 2014) have also been observed when TEPS has been used to measure anhedonia in schizophrenia. Identified by McCabe (2018), a limitation in the TEPS-A subscale is that it may map better onto 'imagining' future events positively rather than capture the motivation to engage in them. Another limitation of TEPS is its restricted generalizability as it provides its own imagined scenarios, e.g. eating out at restaurants, which may not appeal to everyone.

A more recent measure, the DARS, does measure pleasure, motivation and effort sub-components associated with social and physical rewards generated by participants (Rizvi et al., 2015). However, generating one's own rewarding experiences requires cognitive effort, and with working memory problems observed in depression (Fisk et al., 2019), the utility of this questionnaire could be biased by cognitive deficits in depression.

iii. New Developments Towards A Holistic Measurement Framework

Currently available anhedonia questionnaires have not been developed specifically for adolescents and so pose scenarios that may be unrelated or unimportant to adolescent life, such as enjoying "tea, coffee or my favourite drink" in SHAPS and "the sound of crackling wood in the fireplace is relaxing" in TEPS. A qualitative study on the experience of anhedonia in adolescents with MDD identified several themes like lower motivation and enjoyment, which map closely to the reward processing sub-components, but also a loss of sense of self, purpose and agency, a sense of disconnectedness, and emotional flattening (Watson et al., 2020). This suggests that anhedonia in adolescent depression is more than just a loss of interest and pleasure, and indicates social deficits that resembles the negative symptoms of schizophrenia (Millan et al., 2014). This breakaway from a narrow focus on deficits in motivation and pleasure is a recommended change by Fried et al. (2022), who suggest understanding the "nature, breadth and depth" of a construct. This has allowed the identification of over-arching concepts such as disconnectedness from present reality, which may diminish overall reward processing instead of impairing a single sub-component like enjoyment. Granular focus on sub-components may identify this disconnectedness as a deficit in all sub-components but will never be able to identify it *explicitly* using current self-reported measures. Using this insight, Watson et al. (2021) developed the Anhedonia Scale for Adolescents (ASA), based on their earlier qualitative study on anhedonia (Watson et al., 2020), consisting of three subscales: 1) Enjoyment, excitement, and emotional flattening, 2) Enthusiasm, connection, and purpose, and 3) Effort, motivation, and drive. The items and the language are adapted to be understandable for adolescents and do not require subjects to imagine rewarding scenarios. ASA has outperformed the SHAPS and anticipatory subscale of the ACIPS when predicting depression severity measured by the MFQ (Watson et al., 2021). Moderate discriminant validity from anxiety in a high school sample warrants further investigation to see if ASA can distinguish between depression with and without comorbid anxiety. Nonetheless, ASA faithfully measures the experience of anhedonia as described by adolescents themselves and should be considered a useful tool for future research.

While ASA's Subscale 1 measures deficits in enjoyment regardless of context, the Domain of Pleasure Scale (DOPS; Masselink et al., 2019) expands on this by exploring pleasure in real-life domains. Developed in young adults (mean age = 21 yrs), the DOPS captures the enjoyment of domains like social (close friendships, meeting new people), sexual (intimacy, arousal), perceptual (pleasant smells, good meal) and personal achievements (learning new things, hobbies, sports) (Masselink et al., 2019). The DOPS has been applied in previous studies to categorize young people (ages 18-24) into high anhedonia groups (V. E. Heininga et al., 2017; Vera E. Heininga et al., 2017), which was associated with higher negative affect (NA) and lower positive affect (PA) compared to controls. It was also utilised by Van Roekel et al. (2019), who showed that the pathway of PA to motivation is stronger in the anhedonia group vs controls, thereby indicating that deficits in positive emotions may underlie motivational deficits in anhedonia. From this literature, it appears that the DOPS is yet to be used to examine how deficits in domains change with depression symptoms and demographics (age, gender). Further, concurrent use of the DOPS and the ASA would allow researchers to capture anhedonia-related impairments in multiple constructs and domains, respectively. This would help locate impairments more precisely and thereby identify targets for interventions.

iv. Summary

In summary, the SHAPS measures anhedonia as a unitary construct of pleasure experience and studies using it report higher anhedonia severity in MDD adolescents compared to healthy controls. Studies using the TEPS subscales report deficits in anticipatory and consummatory pleasure, in depressed adolescents and adults. However, the TEPS anticipatory subscale only captures positively imagining future reward instead of the motivation to attain them. In evaluating these findings, recall bias must be borne in mind, meaning that in-the-moment pleasure cannot be accurately represented in questionnaires as most are asking about the last week or weeks. Also, personal preferences for standardised rewards, i.e. "crackling of wood in the fireplace is relaxing", may confound ratings of pleasure. The ASA, however, might better capture the real life experience of anhedonia in adolescents that can in turn be mapped to more than one sub-component of the reward system. This, referred to as the positive valence system (PVS) captured by the RDoC initiative, is proposed as the mechanistic underpinning that gives rise to the experience of anhedonia.

1.4.2. Experimental Tasks

Experimental tasks, unlike questionnaires, can present subjects with primary rewards (food, pleasant stimuli). However, similar to questionnaires, standardised rewards are used that cannot be tailored to each subject's preferences and many tasks examining reward tend to use secondary rewards like money, which is not directly related to consummatory pleasure (Kaya & McCabe, 2019; McCabe, 2018).

Briefly, previous experimental tasks have assessed the relationship between anhedonia and depression symptoms, and experiences of anticipatory and consummatory pleasure of rewards. In young people with higher depression symptoms, blunted neural responses have been reported in the anticipatory (Rzepa et al., 2017; Rzepa & McCabe, 2019) and consummatory phases (Rzepa et al., 2017) for primary rewards like chocolate (i.e. rewards in with innate value for survival or reproduction (Sescousse et al., 2013)). Further, greater connectivity between cingulate and insular cortical regions may correlate with higher anticipatory anhedonia (lower TEPS-A) (Rzepa & McCabe, 2016). These neural underpinnings of anhedonia symptoms are reflected in the subjective appraisals of rewards, such as lower "wanting" ratings for primary rewards (imagined social interactions) in young people with higher depression symptoms (Setterfield et al., 2016). Further, lower "liking" and "wanting" ratings for both primary (chocolate, puppy images) and secondary (money) rewards (Frey et al., 2023a) have also been reported in young people with higher anticipatory anhedonia (lower TEPS-A). However, it is also argued that, when between-subject differences in neural responses have been apparent, subjective self-report measures have not been sensitive enough to reflect this (reviewed here: McCabe, 2018).

Developments in EMA (or ESM) (Shiffman et al., 2008) have allowed us to capture real life experiences of anticipatory and consummatory pleasure of activities that subjects *choose* to engage in, instead of standardised rewards that are described above. Although EMA also uses self-report measures, which may be less sensitive in capturing individuals differences as discussed above, it provides a more ecologically valid understanding of reward processing (i.e. how young people process rewards in *real life*). Therefore, this thesis will choose to examine the relationship between depression and anhedonia symptoms, and anticipatory and consummatory pleasure from EMA studies, along with other reward processing sub-components (see '*1.4.3. Experience Sampling Methodology'*).

Nonetheless, experimental tasks continue to have immense utility in measuring impairments in motivation and learning. However, either they cannot be easily measured by self-report measures (learning), or can be better measured objectively (motivation/effort) rather than with self-report measures that are prone to negative biases in depression (Giromini et al., 2022; LeMoult & Gotlib, 2019) and often don't correlate with objective measures, like response times (Akhtar & Firdiyanti, 2023). More specifically, computational modelling can be used to assess parameters, such as a learning rate and temperature, that explain choice behaviour in probabilistic learning tasks; this will be discussed in the '*ii. Learning*' and '*iii. Computational Modelling*' subsections. Further, objective measures of effort exertion, *willingness* to exert effort for a given reward and *perception* of the effort that was exerted can provide extra information about motivation and effort in experimental tasks. Therefore, this section will focus on the research on motivation, effort and learning in adolescent depression, their relationship with anhedonia, identify limitations in currently available tasks and report on new developments.

i. Motivation & Effort

Using behavioural tasks, motivation is considered to be a product of the computation of the value of the reward and the effort needed to acquire it, that leads to goal-directed behaviour (or effort exertion) (Kring & Barch, 2014; Thomsen, 2015; Treadway & Zald, 2011). As such, motivation and effort mediate the anticipatory and consummatory pleasure sub-components of reward processing (Figure 1) (Kring & Barch, 2014), representing the processing and execution of appropriate behaviour to acquire reward. Therefore, the two sub-components are inextricably linked, so motivation and exertion of effort are being considered together here.

A long history of examining motivation in the preclinical literature exists mostly in studies of drugs of addiction, where animals exert effort on progressive ratio tasks to gain access to reward (Cambre et al., 2023; Kuhn et al., 2019). More recently, studies have also begun to measure physical effort for reward, to examine the relationships between depression and anhedonia symptoms and effort exertion using button presses (Rzepa et al., 2017) or using a dynameter (hand squeeze) (Cléry-Melin et al., 2011), and cognitive effort using Working Memory tasks (Liu et al., 2016) and Stroop tasks (Holmes & Pizzagalli, 2010) to name a few.

A task that incorporates effort-based decision making along with button presses for effort exertion is the 'Effort-Expenditure for Rewards Task' (EEfRT; Treadway et al., 2009). Participants are informed of the probability of winning different amounts of monetary reward and are required to choose either a low or high effort option that leads to it. EEfRT captures processing of reward value (magnitude and probability of acquiring it) and the associated effort (low or high), so the proportion of high effort decisions at different win probabilities of high reward provides an objective measure of motivation. Most studies found an association between anhedonia and reduced selection of the high effort option in both young people (Bryant et al., 2017; Olino et al., 2021; Slaney et al., 2023; Treadway et al., 2009) and adults (Darrow et al., 2023; Geaney et al., 2015; Treadway et al., 2012; Yang et al., 2014), especially for anticipatory anhedonia (TEPS-A scale) (Darrow et al., 2023; Geaney et al., 2015; Yang et al., 2014). Some studies report this only in low and medium win probabilities of high rewards (Geaney et al., 2015; Treadway et al., 2009) but that the high effort option, regardless of symptom severity, is chosen if the win probabilities are high (Renz et al., 2023; Slaney et al., 2023; Treadway et al., 2009). It can be speculated that medium and low win probabilities could emulate daily life better as achieving a desired reward is almost never a guarantee, and so results at lower win probabilities can be extrapolated to real life. This indicates that individuals, who anticipate less pleasure from future rewards, will associate lower value to rewards and so only accept a lower effort cost in acquiring them. This is consistent with the reports of poor motivation in adolescents when describing their experience of anhedonia (Watson et al., 2020).

Similar to EEfRT, tasks with progressive ratio schedule (PRS) of reinforcement have also been used to examine motivation. These tasks determine the “breakpoint” of effort exertion (e.g. total number of button presses) where incrementally greater effort is needed to acquire greater rewards (e.g. more money/food) (Fussner et al., 2018) and a higher breakpoint represents higher approach motivation. Though in a small sample of just six undergoing depression treatment, Hughes et al. (1985) reported that a greater increase in the breakpoint of toggle switch presses to acquire monetary rewards was observed in participants with a greater reduction in depression symptoms. Fussner et al. (2018) also demonstrated that, compared to HCs, depressed individuals showed a lower breakpoint for monetary and social feedback rewards but higher for food in university students. This indicates that primary and secondary rewards may differentially influence motivation impairments in depression, and not always with deficits in the sub-component as would be expected. Therefore, incorporation of primary rewards in experimental tasks can help evaluate how motivation might differ across different reward types (reviewed and identified by Rizvi et al., 2016). With partially dissociable brain regions representing primary (anterior insula) and secondary rewards (anterior orbitofrontal cortex) (Sescousse et al., 2013), it supports the idea that motivational deficits can differ between different types of reward. Additionally, current PRS and EEfRT literature focuses on adults with depression symptoms (Geaney et al., 2015; Slaney et al., 2023) or with MDD (Cléry-Melin et al., 2011).

Both of these limitations are addressed by Rzepa et al. (2017) who assessed effort investment by young people with anhedonia symptoms to acquire a chocolate reward. Adapted from McCabe et al. (2010), the task contained the anticipation (picture of chocolate), effort (number of button presses) and consummation (tasting chocolate) phases. Although Rzepa et al. (2017) reported no differences between high and low depression risk groups in effort investment, their later study with a much larger sample showed lower investment by adolescents for a chocolate reward at higher anticipatory anhedonia (lower TEPS-A) (Rzepa & McCabe, 2019). Further, adapting a reward and effort learning task by Skvortsova et al. (2014), Frey et al. (2023a) examined effort exertion using a dynameter for primary (puppy images, chocolate) and secondary (money) rewards in young people. At each trial, participants were given a high or low effort bar, that had to be filled by squeezing the dynameter to achieve the reward. For high effort trials, Frey et al. demonstrated that higher consummatory anhedonia (lower TEPS-C) correlated with higher effort completion times across all reward types, i.e. effort took longer to complete implying lower effort exertion. Together, these studies demonstrate deficits in physical effort exertion at higher anhedonia symptoms, regardless of reward type but, due to the small number of studies, replication of these effects should be explored. In addition, these tasks place effort between the anticipatory and consummatory phases of reward processing, such that they emulate the real-life experiences of motivation and effort processing.

While most studies discussed above have used physical effort as a measure of motivation and effort, some employed cognitive effort paradigms. A systematic review of effort studies reported no relationship with anhedonia symptoms in non-clinical samples with cognitive effort, but showed reduced cognitive effort in MDD and dysphoric groups (Horne et al., 2021). More recently, deficits have been reported in willingness to exert cognitive effort (spatial working memory task) in MDD (Ang et al., 2023). However, the Horne et al. review listed just three studies showing this relationship and so indicated no robust findings but reported ample evidence to show reduced physical effort with depressive and anhedonia symptoms, supporting the findings of studies discussed so far in this section.

The only study to compare both effort types, Tran et al. (2021) used the EEfRT task paradigm for MDD participants to exert physical (button presses) and cognitive (N-back working memory task developed by Harvey et al. (2005)) effort in two separate iterations. Interestingly, the study showed that lower physical effort was associated with higher anhedonia symptoms, as expected, but that lower cognitive effort was associated with poor life functioning, i.e. relationships, job performance. So, although little focus on cognitive effort in motivation research may explain why no robust relationships with anhedonia symptoms have yet been observed, it may also be the case that only impairments in physical effort are associated with anhedonia.

In summary, the EEfRT and PRS tasks have used physical effort paradigms to measure the motivation and effort associated with monetary rewards, where most of the research shows depression- and anhedonia-related deficits. Recent studies using primary rewards (chocolate or pleasant stimuli, like puppy images) have also captured effort exertion in its context in accordance with the TEP cycle (Figure 1), i.e. between the anticipatory and consummatory reward processing sub-components, which should be replicated in more studies. As the relationship between anhedonia symptoms and cognitive effort remains unclear, the use of physical effort should be favoured.

ii. Learning

Reward learning, or learning to maximizing rewarding outcomes, is based on taking an action, predicting and then receiving an outcome, updating the value of the action, and then adjusting the action accordingly (Berridge & Robinson, 2003). In this subsection, the research investigating how reward learning is associated with depression and anhedonia symptoms will be discussed along with any new developments in learning tasks. To identify underlying mechanisms of learning impairments that govern observed behaviour, we will also rely on studies that computationally model behavioural data, where parameters (capturing aspects of learning, such as learning rate, reward sensitivity, etc. (Eckstein et al., 2022)) and their relationship with symptoms are discussed. These would present potential treatment targets and will be interpreted independent of task structure.

One such task is the Probabilistic Reward Task (PRT, or signal detection task) developed by Pizzagalli et al. (2005) in university students, which presented participants with a mouthless face per trial and required them to select between a ‘long’ or ‘short’ mouth. One option was asymmetrically reinforced three times more than the other with positive feedback of a monetary reward. A change response bias towards choosing the more reinforced option, between the final and first block of trials, was operationalised as a measure of reward responsiveness, indicating how history of reward reinforcement modulated behaviour. Pizzagalli et al. demonstrated that individuals with elevated BDI (score >16) failed to show a response bias and also showed higher anhedonia symptoms at a 1-month follow-up. These findings were supported in adult (Esfand et al., 2024; Liu et al., 2011; Liu et al., 2016; Pechtel et al., 2013; Pizzagalli et al., 2008; Vrieze et al., 2013; Whitton et al., 2020) and adolescent samples (Ngan et al., 2023; Pizzagalli et al., 2008). Vrieze et al. showed that greater blunting of response biases predicted poorer response to MDD treatment, Pechtel et al. demonstrated how this persists after remittance, and most studies showed the specific association of blunted biases with higher anhedonia symptoms. Together, these studies, with the exception of some conflicting findings (Blain et al., 2021; Boger et al., 2014; Darrow et al., 2023; Frank et al., 2019; Reilly et al., 2020), showed that a history of reinforced stimuli fails to alter behaviour towards optimising rewards (or poor reward learning) in depressed and anhedonic individuals.

Reversal-learning tasks also demonstrate inflexibility in choice behaviour. Presented with two options, participants are more frequently rewarded with money when selecting one option than the other. Following this, contingencies are reversed at some point in the task, which initiates instrumental extinction and allows for the assessment of how choices change upon this change in feedback. Following reversal of contingencies, a lower rate of selecting the more rewarding option was observed in MDD compared to healthy controls (Mukherjee et al., 2020; Robinson et al., 2012), and adjustment of choices to new contingencies were also slower (Mukherjee et al., 2020). These studies demonstrated the same difficulty in adapting behaviour to avoid punishment (monetary loss) in MDD. Further, ‘misleading’ negative feedback (i.e. occasional punishment for selecting the usually rewarding option) lead to more frequent switching to the alternative option in depressed individuals (Dombrovski et al., 2015; Murphy et al., 2003; Taylor Tavares et al., 2008). This may indicate either an oversensitivity to unexpected aversive feedback or less robust learning from the reinforced option, leading to a failure of sticking to these choices in depression.

Probabilistic instrumental learning tasks are similar to the reversal tasks, but without instrumental extinction, and replicate the real-world behaviour of attempting to maximize rewards. One such task is a reward learning task developed by Pessiglione et al. (2006), with monetary rewards probabilistically associated with two options, was used by multiple studies (Admon et al., 2017; Kumar et al., 2018). As shown before with the signal detection tasks, MDD groups showed poorer reward learning compared to healthy adults. Despite some studies reporting no impairments in reward learning (Rothkirch et al., 2017), the studies discussed above support the findings of literature reviews that indicate poorer reward learning associated with higher depression and anhedonia symptoms (Kangas et al., 2022; Thomsen, 2015).

iii. Computational Modelling

Beyond these known impairments in reward learning, computational modeling of choice behaviour can elucidate certain aspects of learning that may be impaired in depression, that are not apparent from behavioural measures like task performance. The most commonly used reinforcement learning algorithm is Q-learning (Watkins, 1989), which includes free parameters in the *learning* and *decision-making* phases that can then be correlated with symptoms (or compared between groups).

Within the *learning* phase (Equation 1), the discrepancy between the actual ($R(t)$) and expected reward ($Q_A(t)$) of the chosen option provides the prediction error ($R(t) - Q_A(t)$), which contributes to updating the value of the chosen option for the next trial ($Q_A(t+1)$). Relevant to reward processing, parameters included at this phase are learning rate (α, the impact that unexpected outcomes have on updating the value associated with chosen option) and outcome sensitivity (ρ, an individual's intrinsic representation of the rewards ($R(t)$); discussed above in signal detection task) (Equation 1).

$$\boldsymbol{Equation\ 1}: Q_A(t+1) = Q_A(t) + \alpha\ (\ \rho\ R(t) - Q_A(t)\ )$$

The *decision-making* phase is structured as a SoftMax equation (Equation 2A, B), producing the probability of the selected option ($P_A(t)$) being chosen according to the model at each trial, considering also the value of the unchosen option ($Q_B(t)$). The most relevant and widely used parameter is temperature (τ or β, the importance given to learned values of options when deciding which to choose; also referred to as the explore/exploit parameter).

$$\textbf{Equation 2A}: P_A(t) = \frac{e^{\frac{Q_A(t)}{\tau}}}{e^{\frac{Q_A(t)}{\tau}} + e^{\frac{Q_B(t)}{\tau}}}$$

$$\textbf{Equation 2B}: P_A(t) = \frac{e^{\beta\, Q_A(t)}}{e^{\beta\, Q_A(t)} + e^{\beta\, Q_B(t)}}$$

Choice behaviour from the studies discussed in this section have been computationally modelled. A reinforcement learning meta-analysis by Huys et al. (2013) used behavioural data from 392 sessions of signal detection tasks. As discussed above, depressed individuals appeared to fail to develop a response bias towards the more often rewarded option. Huys et al. demonstrated that this may be due to poorer outcome sensitivity (ρ) in anhedonic depression, in that rewards are intrinsically experienced as being less rewarding in MDD individuals with higher anhedonia symptoms. Brown et al. (2021) showed the same anhedonia-related deficits, which are in line with the deficits in the consummatory pleasure (or 'liking') sub-component of reward processing (discussed in '*1.4.1. Self-Report Questionnaires*'). This indicates that rewarding experiences are less pleasurable in depression, whereby behaviour is less prone to changing as a function of reward, which is observed as poorer reward learning.

Interestingly, Huys et al. also suggest that this reward insensitivity may also be expressed by impairments in temperature (β; Equation 2B), such that lower 'β' reflects more exploratory choices in anhedonic MDD, thus failing to 'exploit' the more rewarding option and 'exploring' the lower-valued alternative. This over-exploration of options (or under-exploitation of reinforcement history), also referred to as higher choice stochasticity to reflect the random choices being made, has been reported in participants with depression symptoms (Kunisato et al., 2012) and MDD patients (Pike & Robinson, 2022; Rupprechter et al., 2018). However, a systematic review examining temperature parameters demonstrated mixed findings, with both greater exploration and exploitation at higher depression symptoms, as well as no association between temperature and depression symptoms (Lloyd et al., 2024), akin to the inconsistent results for outcome sensitivity discussed above. Conflicting findings of lower (Brown et al., 2021; Mukherjee et al., 2020; Safra et al., 2019; Shen et al., 2024) and no difference (Bansal et al., 2025; Gradin et al., 2011; Kumar et al., 2018) in learning rates in depressed individuals, compared to controls, are also seen throughout the literature.

Finding impairments in parameters in the learning or the decision-making phase can indicate whether cognitive or behavioural interventions, respectively, may be more effective. However, no consistent evidence of impairments in any of the parameters makes it difficult to arrive at any conclusions thus far. Further, to date, most tasks have focused only on maximizing rewards and/or minimizing punishment, but have not captured the real-life reward processing sub-components described in the TEP cycle (Figure 1): making decisions that maximize rewards and then exerting effort that leads to those rewards. So, in the next section, new developments in tasks to measure reward function will be discussed alongside the advances being made in understand learning about effort for reward.

iv. New Developments

Skvortsova et al. (2014) developed an instrumental learning task, where a choice is made between two options leading to an outcome, which is the combination of a reward and an effort level. After exerting the required physical effort, using a dynameter, a monetary reward was obtained per trial. Both reward and effort were split into high and low levels, and each had different contingencies attached to it. Effort was calibrated per subject using baselines trials that required maximal force (Fmax), then 80% and 20% of Fmax of each subject were designated as high and low effort, respectively. For example, between the left and right option, the high reward (20 cents) had a contingency split of 75%/25% and the high effort was set to 100% for both options. With this, they captured reward learning, in that high effort is fixed for both options but reward is asymmetrical, and so subjects are required to learn the option the leads to maximizing rewards while also exerting effort. The novelty here is that this task also captures effort learning, i.e. high rewards may be fixed for both options but high effort is kept at an asymmetrical split, and so the aim is to minimize effort.

This paradigm is also ideal for investigating anhedonia-related impairments as it uses physical effort, in which deficits have already been identified (see *'i. Motivation & Effort'*, and Horne et al. (2021)).

Using this task, Skvortsova et al. (2014) identified that brain regions encoding expected rewards and efforts were dissociable in frontocortical regions in healthy individuals. Vasilisa Skvortsova et al. (2017) also demonstrated this dissociation in patients with Parkinson's Disease (PD) on dopaminergic medication who showed better reward learning compared to those without medication, but no differences in effort learning. As dopaminergic deficits are known to underlie anhedonia in MDD (Belujon & Grace, 2017; D'Onofrio et al., 2024), these findings indicate that an impaired ability to maximise reward could underpin depression and anhedonia symptoms but how learning to minimize effort might be related to symptoms is still unclear.

To this end, Frey et al. (2023a) adapted this task to provide both primary (chocolate, puppy images) and secondary (monetary) rewards. Examining the association between learning and anhedonia symptoms in young people, Frey et al. showed poorer reward learning at higher anticipatory anhedonia, measured using the TEPS-A, and overall significantly better reward learning than effort learning across all reward types. The absence of any relationship between effort learning and anhedonia symptoms may suggest selective impairment of reward learning, but confirming its validity requires further investigation.

However, the finding that all participants were significantly worse at minimizing effort than maximizing reward may be due to a methodological limitation in these studies. Along with Skvortsova et al. (2017; 2014), Frey et al. had an interleaved structure of reward and effort learning trials, and the contingencies were counterbalanced between them, so participants' attention had to switch at each trial and performance in one may have come at the cost of the other. Frey speculated that the inclusion of primary rewards may have made the reward outcomes more salient than the effort outcomes, leading to better overall performance in acquiring rewards. However, the use of primary rewards, like pleasant images, are a welcome change from the use of secondary rewards (money) in most studies that were discussed in *'ii. Learning'* section. A meta-analysis of fMRI studies has demonstrated that neural correlates of primary and secondary rewards are partially dissociable

(Sescousse et al., 2013), which suggests the possibility that depression and anhedonia symptoms may differentially affect processing of different reward types. Therefore, further investigations are needed with primary rewards in this task paradigm. Further, future task designs must ensure that there is no competition between learning to maximize reward and minimize effort, which was a result of interleaving reward and effort learning trials. Dividing these trials into separate reward and effort learning blocks would alleviate this competition.

v. Summary

Future directions in experimental tasks have been identified in the '*iv. New Developments*' section. Adapting the instrumental learning task used by Frey et al. (2023b), original research in this thesis will examine the relationship between reward and effort learning, and depression and anhedonia symptoms. So that participants' attention need not switch between effort and reward learning at each trial, which lead to poorer effort learning compared to reward learning (Frey et al., 2023b), the interleaved structure of the trials will be altered by dividing them into blocks. Each trial's structure also captures the TEP cycle (Figure 1), where a future reward is anticipated, leading to effort exertion and reward consummation. In addition, computationally modeling the choice behaviour would help identify the aspects of learning that are impaired with depression and anhedonia symptoms.

1.4.3. Ecological Momentary Assessment

While questionnaires and tasks only allow examination of reward processing components within a lab-based context, ecological momentary assessment (EMA), or experience sampling methodology (ESM) (Shiffman et al., 2008), allows the assessment of mood and behaviour in real world contexts and in real time. Participants complete self-report questionnaires, reporting various aspects of their in-the-moment experience of real-life events. In this section, momentary experiences of reward processing sub-components will be discussed and their association with depression and anhedonia symptoms, and what is as yet unexamined in young people. A unique benefit of EMA is that it removes the recall bias that is inherent in questionnaires, so how much participants engaged in certain activities can be gauged more accurately. As altering behaviours, like reducing sedentary behaviour (Kandola et al., 2020) and increasing engagement in positive social interactions (Setterfield et al., 2016), are shown to reduce the future risk of depression (Liu et al., 2025; Zhai et al., 2015), it is clear that identifying the sub-components of reward that might drive activity engagement could reveal targets for treatments. Therefore, how symptoms and momentary reward processing are associated with activities will also be reviewed.

i. Reward Processing & Affect

First, the literature on the overall relationship between reward processing sub-components and symptoms will be reviewed. Only two studies have investigated the momentary experiences of both anticipatory and consummatory pleasure in depression using EMA, and report deficits in both sub-components in dysphoric adolescents (Li et al., 2019) and MDD adults (Wu et al., 2017). Using a dimensional approach, Bakker et al. (2017) reported that young people's experience of reward "anticipation" was lower, and Brown et al. (2011) demonstrated that university students rated lower enjoyment of current activity, at higher depression severities. Across these studies, anticipatory pleasure was assessed using similar questions: participants select the activity they expect to do in the next 1-2 hours, from multiple choices, and rate how much pleasure they anticipate experiencing on a 100-point slider scale (Wu et al., 2017), on a visual analogue scale between 1 and 10 (Li et al., 2019), or on a 7-point Likert scale (Bakker et al., 2017). The same multiple choices of activities and ratings scales were used for assessing in-the-moment enjoyment of the chosen activity. Further, Wu et al. (2017) used 0 to +50 as a rating for pleasure and 0 to -50 for displeasure, finding that the experience of displeasure across all activities were higher in MDD adults compared to controls. Similar findings across various self-report methodologies suggests that deficits in the experiences of reward-related pleasures are consistent in depression.

Beyond the sub-components, EMA studies have also assessed the momentary experiences of positive and negative affect (PA and NA), which is a measure of mood (Manjunatha et al., 2009; Sims, 1988). The momentary experiences of PA, considered to be a measure of an individual's hedonic capacity (Bogdan & Pizzagalli, 2009), are shown to be lower in young people with anhedonia compared to non-anhedonic controls (Heininga et al., 2017), and in MDD adults (Bylsma et al., 2011;

Heininga et al., 2019; Thompson et al., 2012). As expected, dimensional analyses have also consistently shown that lower momentary PA is associated with higher depression severities (Bakker et al., 2017; Brown et al., 2011; Dejonckheere et al., 2018; van Roekel et al., 2016). These studies have used items that capture a variety of arousal states of PA, as conceptualized by the circumplex model of affect (Russell, 1980). These include adjectives associated with low (relaxed, happy, satisfied) and high (euphoric, enthusiastic, energetic) states. Similarly, higher momentary experience of NA is associated with higher depression severities across low (sad, lonely) and high (anxious, irritable, angry) arousal states (Brown et al., 2011; Bylsma et al., 2011; Dejonckheere et al., 2018), representing the "depressed" mood that is analogous with depression. Therefore, we may surmise that deficits in the real-life experiences across all arousal states of PA, higher NA, and lower anticipatory and consummatory pleasure are associated with higher depression severities, as expected. However, the association with anhedonia and the momentary experience of other sub-components remains unclear.

ii. Affective Reactivity & The Mood Brightening Effect

EMA can also assess how self-reported experiences may drive activity engagement and how activities can drive affective experiences. Brown et al. (2011) assessed with whom participants spent their time at eight timepoints per day for seven days and reported that young people with higher depression symptoms spent more time alone. They also reported that, when with others, momentary experiences of consummatory pleasure were lower, and a preference for being alone was higher. Young people with depression symptoms also reported feeling a greater sense of social distance, and that they had to be alone as they were not "wanted" by others (Brown et al., 2011). This suggests that one driver of loneliness in young people could be a perception of social rejection and higher disconnectedness from others in social contexts. Pertaining to reward processing, greater "preference" for being alone, indicates lower motivation for socialising, and deficits in enjoyment of social contexts, consistent with reports by adolescents with anhedonia (Watson et al., 2020). This comprehensive study also examined the effects of socialising on momentary affect, and found higher PA and lower NA when with others, compared to when alone, regardless of depression severity (Brown et al., 2011). Also, the "closer" the young people felt to others, they experienced higher PA and lower NA. Interestingly, these correlations were stronger in young people with higher depression symptoms, indicating that depressed young people showed greater elevations in mood when engaged in social interactions.

A more elevated mood in depressed individuals in positive events, or the "mood brightening" (MB) effect, has been examined in other EMA studies. This, however, goes against the current understanding of lower NA and PA reactivity to reward using lab-based stimuli in depressed individuals (Bylsma et al., 2008; Rottenberg et al., 2005) and the finding of emotional flattening in anhedonia in adolescents (Watson et al., 2020).

Peeters et al. (2003) examined both PA and NA reactivity. They first observed an MB effect where events, appraised as being positive by participants, predicted a positive PA reactivity (i.e. increase) in both MDD and control adults, but a greater increase in MDD. Similarly, for negative events, PA showed greater negative reactivity (i.e. reduction) in MDD. By contrast, NA was less reactive in MDD regardless of event appraisal. Together, these findings show that PA may be the more reactive construct to daily activities, suggesting that the MB effect may be driven by a greater increase in PA in depressed individuals.

More recent affective reactivity literature presents contrary findings. PA reactivity to positive events is shown to not differ between anhedonic and non-anhedonic individuals (Heininga et al., 2017), and no differences in PA reactivity is also reported in MDD adults (Bylsma et al., 2011) and young people (Thompson et al., 2012). However, greater negative NA reactivity (i.e. decrease) to positive events was demonstrated by these studies (Bylsma et al., 2011; Thompson et al., 2012), and Heininga et al. (2017) demonstrated greater decreases in NA in the anhedonia group vs non-anhedonic controls. Moreover, C. S. M. Wong et al. (2024) showed greater positive NA reactivity (i.e. increase) to environmental stresses (discomfort, desire to leave current environment) in depressed adults compared to controls. Further, van Roekel et al. (2015) showed that lonelier adolescents experienced greater increases in NA when experiencing social stress (feeling threatened and judged by social company). These findings, therefore, indicate that the brightening effect may be driven by NA.

Further, reflecting developments in this area, Heininga et al. (2019) assessed PA reactivity to specific *activities*, instead of subjectively appraised events. They showed that PA to potentially rewarding activities (sport, hobbies, friends, partner) did not differ between controls and MDD. The most comprehensive study of the MB effect, however, was by van Loo et al. (2023) who examined social and physical activities separately, and assessed both PA and NA reactivity. They found that the MB effect of being "physically active outdoors" was driven only by a larger decrease in NA in depressed individuals, whereas *both* an increased PA and a reduced NA drove the MB effects of "socialising". This hints at affective specificity to different real-life contexts, a possibility not explored by other studies to date.

Given the small number of studies examining PA and NA reactivity to activities in real-life with EMA, it is still unclear how affective reactivity might underpin symptoms such as anhedonia. Further, future research needs to also address the many inconsistencies in methodologies across studies. First is to address the differences in how positive activities are operationalised, as some studies report on the subjective appraisal of events whilst others report on specific events (e.g. sport, hobbies) as discussed above regarding Heininga et al. (2019) and van Loo et al. (2023). Greater clinical utility could come from identifying the specific activities that depressed individuals should be encouraged to engage in, and the drivers of such engagement could then be revealed and targeted for clinical improvements in mood.

Second is to identify the mechanism by which mood brightening occurs, as the differences in which affective constructs drive the MB effects of social and physical activities is as yet unclear. It is possible that leisure activities and social interactions, considered to be 'hedonic' (elevate PA) (Pressman et al., 2009), may more effectively reduce NA in depressed individuals and thus improve mood. Knowing this could help clinicians inform participants about how engaging in these activities through interventions such as behavioural activation (BA; Veale, 2008), may boost mood, thereby strengthening commitment and, therefore, exposure to these rewarding activities.

Third is to consider how affective reactivity is operationalised. Some studies measure reactivity as the momentary NA (Heininga et al., 2017; Panaite et al., 2019) or PA (Heininga et al., 2017) whilst others measure the *change* in NA and PA from the within-subject mean (Bylsma et al., 2011) or from the previous timepoint (t-1) (Khazanov et al., 2019; Thompson et al., 2012). Using different ways of measuring affectivity reactivity can lead to different outcomes, such that comparing momentary affect to the mean could provide clinically useful results, for e.g. knowing the activities that decrease NA and increase PA compared to an individual's average levels could inform treatment. Additionally, examining changes in affective reactivity compared to the previous timepoint can inform the *direction* of temporal change. This is more informative than just examining the mean magnitude of change in affect, measured using the mean squared successive difference (MSSD; Jahng et al., 2008). This only allows for between-subject comparisons, but not for within-subject assessment of the impact of engaging in leisure activities on temporal instability of affect. Studies, using MSSD, demonstrate that poorer well-being is associated with higher NA and PA instability (Houben et al., 2015), and that greater NA instability predicts higher depression symptoms (Bowen et al., 2013; Sultson et al., 2024; Thompson et al., 2012) and greater suicidal ideation (Jeong et al., 2021). Therefore, identifying activities identifying activities that stabilise emotions, or even help elevate mood (i.e. reduce NA or increase PA between consecutive timepoints) can be beneficial.

Further, meta-analyses have shown that temporal instability, when measured using MSSD, does not add value over mean levels and variance of affect in predicting depressive symptoms (Dejonckheere et al., 2019). This suggests that alternatives to the MSSD should be explored to examine if affective dynamics are significantly associated with depression symptoms.

Finally, conspicuous by their absence are studies investigating the association of affective reactivity with anhedonia symptoms. Previous studies have characterised anhedonic individuals as those experiencing persistent pleasure loss (Heininga et al., 2019; Heininga et al., 2017), but not its severity on a dimensional scale. Therefore, how uplifts in PA to rewarding activities are affected by higher anhedonia symptoms remains unclear. This thesis will aim to address this.

iii. Time-Lagged Relationships: Does Activity predict Affect?

As EMA assesses experiences at multiple timepoints, we can examine the temporal relationships between affect and activities between consecutive assessments. In the *'Time-Lagged Relationships'* subsections, this thesis will discuss the relationships between affect and engagement in activities, and how depression symptoms effect these temporal relationships.

In this subsection, the models have the activity at the previous timepoint (t-1) as the predictor and current PA and NA (t) as the outcome, identifying how activities drive affect. Further, the trajectory of affect over several timepoints will be assessed, which will together examine how depression symptoms impact the lasting change in affect following engagement in an activity. It is important to note that all studies ensure that only consecutive assessments within a day are considered, in that the last assessment of day 1 and the first assessment on day 2 are not considered for temporal analyses.

Peeters et al. (2003) reported that activities, that were subjectively appraised by participants as being negative at 't-1', drove a greater increase in NA(t) in MDD compared to controls, whereas no relationship with PA(t) was observed. For positively appraised activities (t-1), Peeters et al. showed that they did not drive current NA(t) or PA (t) in MDD any differently to controls. Regarding PA, these findings were consistent, where studies have shown that physical activities and pleasant company (t-1) drive an increase in current PA(t), but that it does not differ between depressed and healthy controls (Heininga et al., 2019; Heininga et al., 2023; Wichers et al., 2012). These findings were apparent across a 90-minute (Peeters et al., 2003) and a 180-minute (Heininga et al., 2023; Wichers et al., 2012) gap between assessments. This demonstrates that the upliftment of PA, following engagement in a positively appraised activity, persists in both depressed and nondepressed individuals.

Regarding the dynamics of affect over several timepoints following positive activities, Wichers et al. (2012) showed that the trajectory of elevated PA degraded more rapidly in MDD compared to controls, whereas Heininga et al. (2019) reported no differences. Interestingly, De Calheiros Velozo et al. (2023) showed that elevated NA, following an unpleasant activity, persisted significantly longer in adults at a higher risk of depression, compared to controls.

Together, these findings indicate that a longer exposure to elevated NA and shorter exposure to elevated PA, triggered by daily events, may underlie the overall negative emotional experience that dominates depression. However, conflicting findings in sparse literature suggests that more EMA studies are required, which must assess both PA and NA, to identify consistent patterns of within-person differences between PA and NA reactivity.

iv. *Time-Lagged Relationships: Future Enjoyment*

In this subsection, this thesis will assess the findings of studies investigating in-the-moment enjoyment as the outcome instead of NA and PA. Using the difference between anticipatory pleasure (t-1) and enjoyment (t) of the same activity to assess the *accuracy* of predictions, where a difference of zero indicates highest accuracy, Wu et al. (2017) showed that controls and MDD groups both accurately predicted enjoyment. Forecasting accuracy over longer time-lags such as next day or week, shows evidence of either no moderating effects of symptoms (Thompson et al., 2017) or an overprediction of negative responses to future activities in dysphoric groups compared to controls (Hoerger et al., 2012). Interestingly, regardless of group, Wu et al. (2017) showed that displeasure was overpredicted (anticipated displeasure was higher than actual displeasure). Taken together, this indicates an elevated negative bias when anticipating future experiences, especially displeasure, that may lead to avoidance of associated activities. This influence of reward processing in shaping future behaviour will be investigated in the next section.

Only two studies are known that investigate the time-lagged relationships between reward sub-component processes (Figure 1) that predict current enjoyment. Li et al. (2019) conducted the most comprehensive models, assessing the time-lagged predictive relationships between anticipatory pleasure (t-1) and enjoyment (t). To isolate this predictive relationship, they controlled for current PA(t), controlling for the impact of mood, and previous enjoyment (t-1), to control for the inertia of enjoyment (trend of enjoyment change persisting over timepoints) may influence current enjoyment (t) (Dejonckheere et al., 2019). Li et al. showed higher anticipatory pleasure predicted higher enjoyment, but the relationship did not differ between dysphoric and non-dysphoric groups of college students. On the other hand, Bakker et al. (2017) investigated the time-lagged relationship between reward 'anticipation' (t-1) and PA(t) (a measure that is akin to enjoyment) but found no moderating effect of depression severity.

These studies had some major limitations. The activity anticipated (t-1) and the actual activity (t) were not the same. The interpretation of their results is thus: anticipating greater pleasure will lead to greater enjoyment, regardless of the activity anticipated at 't-1' and engaged in at 't'. This may be useful in simply increasing anticipatory pleasure, knowing that it will result in greater future enjoyment. However, if an intervention were to repeatedly exploit this predictive relationship, people would need to have the certainty that when they are anticipating the pleasure of an activity, it will result in greater enjoyment of the *same* activity. That "certainty" would be necessary for repeated use of any intervention. Consequently, if a predictive relationship does not exist for the same activity, anticipatory pleasure would be ineffective as a treatment target for increasing enjoyment. Therefore, future studies must investigate this relationship when activities have been "matched" between consecutive timepoints.

Another limitation in both studies is that neither included the motivation sub-component that precede enjoyment in the TEP cycle, despite its role in driving goal-directed behaviours, whereby the cognitive assessment of a reward and the effort required defines the motivational salience of that reward (Michaelsen & Esch, 2023). We know of only one study by Do et al. (2022) that measured excitement (argued to be a measure of motivation) for an anticipated physical activity, and showed that greater excitement predicted greater future enjoyment. However, this study was conducted in healthy adults only and did not measure anticipatory pleasure.

Thus, current research is sparse and lacks detailed models. Therefore, including measures of all appetitive sub-components of reward processing, and examining the time-lagged relationships in young people with a range of depression and anhedonia symptoms, could help identify the strongest drivers of future enjoyment and if this is moderated by symptoms.

v. Time-Lagged Relationships: Future Activities

In addition to identifying the drivers of enjoyment, EMA allows us to identify the drivers of real-life behaviour, something nigh on impossible to measure in a lab setting.

Bakker et al. (2017) was the first to include a measure of active behaviour with the item "I am actively engaged in something", rated on a 7-point Likert scale. They demonstrated that higher reward anticipation(t-1) was a driver of active behaviour (t) but that this relationship was negatively moderated by depression symptoms. This supports previous findings of poorer modulation of behaviour as a function of the pleasure they anticipate from a reward in depression (reviewed here: Pizzagalli, 2014; Treadway & Zald, 2011). This was termed as 'decisional' anhedonia by Treadway and Zald (2011) – a 'decision' to not pursue rewards, likely driven by an overestimation of costs (or effort) required to attain a reward, whose value is also dampened in anhedonia.

Bakker et al. (2017) disproved that simply increasing the depression-related deficits in anticipatory pleasure (evidence reviewed in '*i. Reward Processing & Affect*' subsection) will encourage engagement in activities, showing that the *time-lagged relationship* should itself be the target. A recent study by Bär et al. (2024) in participants with depressive symptoms also demonstrated this, where using mental imagery exercises (taking a 'mental picture' of the positive aspects of an anticipated activity) only improved anticipatory pleasure but not the time-lagged relationship between anticipation and active behaviour. This results in a failure to increase active engagement in the anticipated activity.

Heininga et al. (2023) also investigated the predictors of behaviour in a clinically depressed adult sample, and did however show that higher motivation (t-1) (looking forward to and the intention to get involved) drove greater engagement in behaviours(t) such as being physically and socially active. However, the strength of this predictive relationship seems to be irrelevant to alleviating symptoms as it had no relation to a future improvement in depression symptoms. By contrast to Bär et al., Heininga et al. demonstrated that that increasing motivation, instead of anticipation, may be a more effective driver of active engagement in depressed individuals, but it remains unclear whether this then translates into changes in mood and depression symptoms.

These three studies have defined 'active behaviour' as either being "active" instead of sedentary and alone, or the *degree* to which participants were actively involved in them. Then, perhaps, there is a suggestion that there is a need to identify targets that drive engagement in activities that directly protective effects against depression symptoms. A potential candidate is 'leisure' activities, defined as enjoyable, relaxing and intrinsically motivational (Nagata & Kono, 2022). Engagement in leisure activities are associated with lower depression symptoms in healthy controls (Bone et al., 2022; Chen et al., 2012; Harvey et al., 2010; Lin et al., 2008; Mikkelsen et al., 2010) and patients (Cuijpers et al., 2007; Pickett et al., 2012). Exercising, which may also be enjoyable, also predicts a lower future risk of depression (Cooney et al., 2013; Pearce et al., 2022; Singh et al., 2023). These benefits can also be attributed to the rewarding social experiences that accompany leisure activities (Pressman et al., 2009). Specifically, increasing individual-interpersonal interactions (friends, family), but not group or solitary activities, are shown to alleviate depression symptoms (Solomonov et al., 2019). There is also abundant evidence from systematic reviews that more frequent social interactions provide both concurrent and future protection against depression symptoms (Campbell et al., 2022; Panaite et al., 2021; Pemberton & Tyszkiewicz, 2016), with positive social interactions predicting higher well-being even 10 years later (Panaite et al., 2021).

Therefore, identifying the reward processing sub-components that increase engagement with leisure activities and social company (specifically, socialising in a small group with close acquaintances), could provide new targets for interventions to protect against depression symptoms in youth.

vi. Summary

Consistently, EMA studies have shown that higher depression symptoms are associated with deficits in PA, anticipatory pleasure and enjoyment, and elevated levels of NA. In this section, this thesis identified that leisure activities and social company are known to protect against depression symptoms.

As the sparse research on time-lagged models only had anticipatory pleasure as the predictor, future EMA studies need to identify which of the appetitive sub-components of reward processing (anticipatory pleasure, motivation) drive enjoyment of leisure activities and social company. Further, very few EMA studies have identified how sub-components drive the level of engagement in activities but not what drives engagement in leisure activities and social company. Future studies need to also identify sub-components that drive engagement in these activities that are beneficial for symptoms.

Regarding PA and NA reactivity, the 'mood brightening' (MB) effect phenomenon opens avenues of identifying the mechanism by which leisure activities and social company elevate mood, i.e. by increasing PA or reducing NA. This can address the approach that young people with higher depression symptoms should take to these activities as, for example, individual-interpersonal social (or socialising with a few, intimate friends), instead of group social interactions, are shown to be more protective against depression symptoms (Solomonov et al., 2019). Therefore, understanding the mechanisms underpinning the MB effect will help researchers identify the best approach that most effectively elevates mood. In literature, a 'hedonic' approach aims to increase positive emotions (e.g. hanging out with a large group of friends), while a 'eudaimonic' approach involves "meaningful" activities that improve a sense of well-being (e.g. meaningful conversations with a close friend) (Reis et al., 2000; Steger et al., 2008). How the time-lagged relationships and reactivity are moderated by depression and anhedonia symptoms must also be assessed. This thesis will aim to address these gaps in the knowledge.

In this section, this thesis also identified EMA studies that examine the trajectory of PA and NA over multiple timepoints, in response to engagement in an activity. As this thesis aims to identify treatment targets that increase engagement in these activities, the impact of the activities on mood after engaging in them is outside the scope of this thesis.

1.5. Outlines of the Studies & Papers

To examine reward processing, two studies were conducted, in young people (ages 16-25 years old) recruited from local schools and the University of Reading. The aim was to examine impairments associated with depression and anhedonia symptoms, which may help identify treatment targets and improve the efficacy of interventions.

The first study used an EMA protocol, adapted from Edwards et al. (2018) in schizophrenia, to assess depression-related impairments in pleasure and motivation processing associated with real-life contexts of physical activities and company.

The second study used an instrumental learning task, adapted from Skvortsova et al. (2017; 2014) and Frey et al. (2023b), to examine impairments in learning to maximize reward and minimize effort. From these two studies, three papers were written – Papers 1 and 2 from the EMA study and Paper 3 from the Task study. Each paper, as stated before, aimed at identifying targets whose impairments are associated with depression and anhedonia symptoms. Below, the research questions for each paper, a brief summary of the methodology and the analyses that will answer these questions will be discussed. Note that each study contained several baseline measures of symptoms, to capture depression and anhedonia symptoms.

1.5.1. Paper 1: Examining How Anticipation and Motivation Predict Enjoyment and Engagement in Leisure and Social Company

A clear benefit of the EMA, which assesses real-life experiences at multiple timepoints throughout the day, is that temporal relationships can be examined at the analysis stage that traditional questionnaires cannot provide. Previous EMA studies have conducted analyses that examine relationships between consecutive timepoints, where Li et al. (2019) was the most relevant to the scope of this thesis. Li et al. examined the relationship between anticipatory pleasure (t-1) and consummatory pleasure (t), in dysphoric and non-dysphoric university students. Multilevel linear models found that higher anticipatory pleasure (t-1) predicted higher consummatory pleasure (t), but the relationship did not differ between the groups.

Bakker et al. (2017) included similar analyses that demonstrated that the predictive relationship between anticipatory pleasure (t-1) and ‘active behaviour’ (t) (level of active involvement) is weaker at higher depression symptoms. However, as identified above in section **1.4.3.***v.*, identifying reward processing sub-components that increase engagement in leisure activities and social company needs to be considered, as these would be the most effective in protecting against depression symptoms.

Limitations of these studies was that they examined only anticipatory pleasure as the predictor, not motivation, and that neither examined drivers of activity engagement. Therefore, examining which appetitive sub-component of reward processing (anticipation, motivation) drives engagement and enjoyment in leisure activities and social company would enhance current understanding.

To do so, an EMA protocol was adapted from Edwards et al. (2018), that captured motivation using questions on preference (“Would you prefer to do something else?”) and interest (“How interested are you in this activity?”) of the planned activity, in addition to the cognitive and affective aspects of anticipation, anticipatory pleasure and expectation, respectively. Further, participants selected the company and physical activities they were engaged in, and rated how much they enjoyed it. To examine time-lagged relationships, multilevel linear models were used for enjoyment as outcome (rated on a 1-7 Likert scale). Multilevel logisitic models examined which sub-components drive behaviour, where the outcomes were binary: Leisure (relaxing, exercising) vs. Functional (work/school, hygiene, etc.) or Social (friends, family) vs. Non-Social (alone).

1.5.2. Paper 2: Examining The Mood Brightening Effect of Leisure Activities and Social Company

Another advantage of EMA is that momentary experiences of mood and how they react to real life contexts can be tracked. Several studies have used this to examine how mood, a composite of positive and negative affect (PA and NA), reacts to subjectively-related contexts. Previous research leaves some questions to answer that this paper will address (discussed in section **1.4.3.***ii.*).

A review of the literature showed that most studies have examined affective reactivity to activities that were subjectively appraised as being positive. A phenomenon of the mood brightening (MB) effect has been demonstrated in some of these studies, in that mood is elevated more in those with higher depression symptoms in response to positive events (higher PA or lower NA or both) (for example, Bylsma et al., 2011; Khazanov et al., 2019). However, conflicting evidence that disproves the MB effect have also been shown, so its validity is in question. Further, there was no consistency in how these studies measured reactivity (section **1.4.3.***ii.*), where some measured it just as momentary affect, while others measured it as the *difference* between momentary affect and baselines, such as affect at the previous assessment (or, t-1) and mean affect.

As far as is known, Heininga et al. (2019) and van Loo et al. (2023) were the only studies that examined reactivity to *actual* activities, such as exercising, being outdoors and socialising. Between them, van Loo et al. (2023) was the only study that examined the reactivity of both PA and NA in participants, while Heininga et al. only assessed PA. Also, van Loo et al. was the more extensive study as it assessed reactivity to physical and social contexts *separately*. They demonstrated that NA reactivity may underlie the MB effect of both physical activities and socialising, with PA reactivity additionally playing a part in socialising. This contrasted with Heininga's findings, who showed no differences in PA reactivity between MDD and controls. Thus, these studies reported conflicting evidence on the MB effect, again questioning its validity. Nonetheless, these studies should be replicated as they would provide more clinically useful results, by identifying activities that can be suggested to young people with higher depression symptoms to more effectively elevate their mood.

Therefore, using the EMA data that included measures of affect, the MB effect of leisure activities and social company was examined. Assessing both NA and PA reactivity within individuals would help identify mechanism that underlies the MB effect.

This study would also build on previous research by measuring affective reactivity as a change from two baselines. Using mean affect as the baseline would aid in assessing how engaging in leisure activities and social company changes mood from an individual's "general" mood. Using affect (t-1) as the baseline, the reactivity would provide a measure akin to temporal instability, which has often been measured using the Mean Successive Squared Difference (MSSD; Jahng et al., 2008) in previous research (Dejonckheere et al., 2019). MSSD collapses the differences in affect between consecutive assessments into a subject-level mean. As a result, the impact of contexts on instability has remained unexamined; this has also been identified as a gap in understanding by a review of reactivity literature (Dejonckheere et al., 2019). Further, NA and PA instability are shown to be associated with poorer well-being (Houben et al., 2015), and greater NA instability is specifically shown to be associated with higher depression symptoms (Bowen et al., 2013; Sultson et al., 2024; Thompson et al., 2012) and greater suicidal ideation (Jeong et al., 2021). As leisure activities (Bone et al., 2022; Chen et al., 2012; Harvey et al., 2010; Lin et al., 2008; Mikkelsen et al., 2010) and social company (Campbell et al., 2022; Panaite et al., 2021; Pemberton & Tyszkiewicz, 2016) can protect against depression symptoms, examining the effect of these activities on temporal instability of NA and PA would extend current understanding and identify mechanisms by which they may reduce depression symptoms.

The analyses in Paper 2 included multilevel linear models, with NA and PA reactivity as outcomes, and an interaction between Activities and Symptoms as the predictors. Same as Paper 1, activities were categorised for Physical activities (Leisure vs. Functional) and Company (Social vs. Non-Social). Along with depression symptoms (measured using MFQ), the Anhedonia Scale for Adolescents (ASA; Watson et al., 2021) was added as a measure of anhedonia symptoms. Controlling for MFQ in the anhedonia models allows for the relationship of anhedonia symptoms with reactivity to be examined in isolation. This build on prior research, as anhedonia had previously only been measured as an 'inability to experience pleasure' criteria in MDD individuals (Heininga et al., 2017; 2019). The interaction effect would determine the MB effect of activities, i.e. how does reactivity change with increasing symptoms in Leisure activities, compared to Functional activities.

1.5.3. Paper 3: Examining Computational Impairments in Reward and Effort Learning

Shifting focus from affect, pleasure and motivation, Paper 3 utilises the reward and effort learning task, developed by Skvortsova et al. (2017; 2014) and adapted from Frey et al. (2023b), to understand how the learning may be impaired in individuals with higher depression and anhedonia symptoms. Frey et al. (2023b) had adapted this task, as discussed in detail in section **1.4.2.***iv.*, using primary (chocolate, puppy images) and secondary (money) rewards, and handgrips for effort exertion. Interestingly, within-subject comparisons demonstrated that individuals were significantly better at maximizing reward than minimizing effort. Frey et al. (2023b) speculated that the interleaved structure of the reward and effort learning trials could be responsible for this, as it means that good performance in one comes at the cost of performance in the other. Therefore, to prevent this competition in learning, reward and effort learning trials were divided into separate blocks for Paper 3.

Moreover, as Frey et al. (2023b) revealed that subjective ratings of liking and wanting of puppy images was level with the ratings for money, and as previous studies have mostly used on monetary rewards (discussed in sections **1.4.2.***ii.* and *iv.*), pleasant images (primary rewards) were chosen as rewards for this study. The binary of high and low rewards was created using puppy and dog images, respectively, as subjects have often rated baby animals as being more ‘pleasant’ than adult animals (Lehmann et al., 2013). The assortment of images that were created by Frey et al. (2023b) were used in this study. The task was adapted for online use, instead of in the lab, by altering the effort component from handgrips to key presses.

Regarding analyses, the choice behaviour in each block modelled using the Q-learning architecture was used (discussed in section **1.4.2.***iii.*). To assess symptom-related impairments, parameters such as learning rate and temperature (or, explore/exploit trade-off parameter) were correlated with anhedonia and depression symptoms. Further, subjective ratings of liking, wanting and effort willingness (a measure of motivation) of the rewards examined the if deficits in reward processing at higher depression and anhedonia symptoms were present. These were measured before and after the task to examine if the wanting, for example, of rewards changed during the course of the task, which may need to be accounted for when modelling the choice behaviour.

This novel task and modelling of behaviour presented the opportunity to examine in which aspect of learning by reinforcement (learning or decision making phases; discussed in section **1.4.2.***iii.*) do depression and anhedonia-related impairments occur when learning to maximize rewards. Identifying these targets may help develop interventions either to improve internal representations of reward or those centred around decision-making.

Further, the task also measured the ability to minimize effort, so modelling would provide the opportunity to examine depression and anhedonia-related impairments when learning about effort. The intrinsic representation of an outcome is an integration of how reward it is perceived to be with the action cost required to achieve it (Devine et al., 2023; Michely et al., 2020). Identifying ways to reduce costs of achieving rewarding outcomes may encourage more frequent engagement with rewards in depressed individuals. This study would extend understanding in this regard, as it would help in identifying the impairments that may obstruct learning to minimize effort.

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2. Paper 1

Anticipation and Motivation as predictors of Leisure and Social Enjoyment and Engagement in Young People with Depression Symptoms: An Ecological Momentary Assessment Study

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Background

Participating in leisure and social activities can alleviate depression symptoms, yet effective strategies to enhance enjoyment and maintain long-term engagement remain scarce. Gaining insight into the reward sub-components that influence daily experiences and drive behaviour could uncover novel targets for intervention.

Objectives

This study examines the role of anticipatory pleasure and motivation in predicting enjoyment and engagement in leisure activities and socializing among young people, and how these relationships are moderated by depression severity, using intensive longitudinal ecological momentary assessments.

Methods

Participants (N=80, mean age = 20 years) used the Psymate2 smartphone app to report mood, enjoyment, current and anticipated activities, and social company seven times daily for six days. Activity categories were relaxation, exercise, other leisure, work/school, studying, chores, shopping, hygiene, eating/drinking, traveling and company categories were partner, friends, family, colleagues, acquaintances, strangers, nobody. Anticipation (anticipatory pleasure, expectation) and motivation (interest, preference) for upcoming activities were rated on Likert scales. Participants were grouped by depression severity, measured using the Mood and Feelings Questionnaire (MFQ): high (HD, MFQ ≥ 27, N=48), moderate (MD, MFQ 16–27, N=16), and low, i.e. controls (C, MFQ ≤ 16, N=22). A total of 2,316 assessments met inclusion criteria.

Results

Leisure activities (relaxation, exercise, other leisure) and being in social company (partner, friends, family) were rated most enjoyable across all groups. Higher depression symptoms were associated with reduced enjoyment of studying (β=-0.03, *P*=.005), eating/drinking (β=-0.02, *P*=.02), and other leisure activities (β=-0.02, *P*=.018), as well as lower engagement in work/school (β=-0.26, *P*=.016) and hygiene (β=-0.08, *P*=.03), and increased inactivity (β=0.17, *P*=.026).

Time-lagged multilevel analyses showed that anticipatory pleasure predicted greater enjoyment across all activities (β=0.12, *P*<0.001) and social contexts (β=0.33, *P*<0.001), with consistent effects in controls and the high-depression group. However, the more an activity was expected to happen, the less enjoyment was experienced, in the whole sample (β=-0.006, P=.001), high-depression group (β=-0.008, P=.001) but not controls.

Anticipatory pleasure and motivation (preference) predicted leisure engagement in the whole sample (β=0.19, P=.003; β=0.11, P<0.001) and controls (β=0.43, P=.005; β=0.17, P=.048) but not the depression groups. Anticipatory pleasure only predicted leisure engagement in the high depression group when predictors and outcomes were matched for the same event (β=0.22, P=.001). Anticipatory pleasure predicted social engagement in the whole sample (β=0.095, P=.047) and controls (β=0.34, P=.003), but not in the depression groups.

Conclusions

These findings highlight the importance of anticipatory pleasure and intrinsic motivation in shaping young people's engagement and enjoyment of daily activities. Structured or externally driven contexts may dampen enjoyment—especially among those with depression—underscoring the need for novel interventions targeting anticipation and motivation to enhance sustained participation in rewarding activities, offering a novel approach to improving well-being in individuals with depression.

Introduction

Major Depressive Disorder (MDD) is a leading cause of disease burden among young people worldwide, yet current treatments offer only moderate effectiveness [1, 2]. A key challenge in depression treatment is that individuals with depression engage less in rewarding activities, likely due to anhedonia - a diminished ability to anticipate and experience pleasure [3-5]. Further, depression also encompasses deficits in the motivation to engage in rewarding experiences [6]. These deficits in reward function could lead to inactivity, which is particularly problematic as reduced engagement in physical and social activities perpetuates symptoms, reinforcing a cycle of low mood and withdrawal. Additionally, loneliness not only increases depression risk [7, 8] but also predicts future antidepressant use [9] underscoring the urgent need for interventions that promote sustained participation in mood-boosting activities [10-14].

A growing body of research highlights the protective role of leisure activities—those that are inherently enjoyable and recreational—in reducing depression rates in the general population [15-19] and in patients [20, 21], compared to functional activities like work or chores. Similarly, social interactions, particularly with close friends and family, appear to be more effective in alleviating depression symptoms than solitary activities or interactions with acquaintances [22]. These findings support the rationale for interventions such as Behavioral Activation (BA), which encourages individuals to increase engagement in pleasurable activities to enhance positive reinforcement [21, 23]. However, despite its effectiveness, BA does not outperform other treatments, likely due to an incomplete understanding of the reward mechanisms that drive sustained engagement [24, 25].

To optimize interventions, a more nuanced understanding of reward function is needed. Reward processing involves distinct sub-components, including anticipation, motivation, and enjoyment, which collectively influence approach behaviour [26, 27]. According to the Temporal Experience of Pleasure (TEP) model, anticipation plays a crucial role in shaping motivation, which then drives behavioural engagement [28, 29].

Reward dysfunction is well-documented in depression [30-32]. For example, higher depression symptoms in adolescents and college students are shown to be associated with lower social pleasure using the Domains Of Pleasure Scale [33], and reduced consummatory pleasure using the Snaith Hamiton Pleasure Scale (SHAPS) [34] and the Fawcett-Clark Pleasure Capacity Scale [35].

We have also found reduced anticipatory and consummatory pleasure in young people with depression using the Temporal Experience of Pleasure Scale (TEPS) [36, 37]. Further, a recent study finds that depressed adolescents have reduced pleasure and motivation for hobbies, food/drinks, social activities, and sensory experiences using the Dimensional Anhedonia Rating Scale [38]. The recently developed Positive Valence System Scale [39] incorporates nearly all the reward subprocesses, such as anticipatory pleasure, consummatory pleasure, motivated behaviour and effort, has shown that deficits in all subprocesses correlate with depressive symptoms in a college student sample [39]. However, inconsistencies across most studies in how reward sub-processes are measured still hinders the identification of specific treatment targets [30, 31, 40].

Lab-based tasks have found lower motivation to exert effort for rewards with increasing depression symptoms in young people [37]. Similarly, studies find that anhedonia is associated with a lower frequency of high-effort choices in a young community sample [41-43] and in young people with subthreshold depression [44]. Taken together, there is certainly evidence for reward sub-component processing deficits in young people that could underpin their depression symptoms. However, traditional experimental tasks still fail to capture the dynamic and real-world nature of reward-driven behaviour [31], leaving critical gaps in our understanding of how anticipation and motivation influence engagement in daily activities and over time.

Ecological Momentary Assessment (EMA) offers a powerful solution to this limitation by tracking real-time experiences within natural environments using smartphone-based assessments [45-48]. EMA studies have demonstrated that social and physical activity protect against depression [49] and that individuals with depression experience fewer positive daily events and social interactions, predicting lower well-being even a decade later [50]. Critically, while one study has shown that anticipatory pleasure predicts subsequent enjoyment of an activity [51], and another found that depressive symptoms weaken the link between anticipation and behaviour [52], these findings remain incomplete. Existing EMA studies have yet to examine motivation as a predictor of activity engagement, despite its central role in approach behaviour. Furthermore, it is unknown whether anticipation and motivation specifically predict engagement in key mood-boosting activities such as leisure and socializing—activities known to be crucial for mental health [53, 54].

To address these gaps, this study investigates how anticipation and motivation influence enjoyment and engagement in leisure activities and social contexts using EMA. Adopting a methodological approach similar to Edwards et al.'s [55] work on schizophrenia, we hypothesize that individuals with higher depressive symptoms will exhibit weaker associations between anticipation, motivation, and subsequent engagement. By providing real-world evidence on the role of reward sub-components in shaping behaviour, this study could identify novel targets for reward-based interventions aimed at improving mental health outcomes.

Methods
Power analysis

We conducted a *priori* power analysis using PowerAnalysisIL designed for EMA [56] using data provided by Li et al., [57] (Table S1, Figure S2). Analysis suggested that 80% power could be achieved with a sample size of 50, consistent with estimates from multilevel logistic [58] and linear models [59] using our design.

Recruitment

Young people (N=95), aged 16-25, with varying depression symptoms, were recruited from local schools and universities. The study adhered to ethical standards (Revised Helsinki declaration 2008) and was approved by the University of Reading Psychology Department Ethics Committee (REC no: 2021-120-CM). All participants provided written informed consent after reviewing the information sheets.

Patient & Public Involvement and Piloting

Based on feedback from piloting sessions with young people, we revised the activity categories and allocated time for app troubleshooting in our study briefing sessions.

Baseline Demographics

Participants completed the Mood and Feelings Questionnaire (MFQ; ≥27 cut off for clinical depression) [60]. Higher scores indicate higher depression symptoms. The 33-item questionnaire has been shown to have excellent internal reliability in adolescents (Cronbach's α = 0.91 to 0.93) [61]. It is a widely used and a validated questionnaire to examine depressive symptoms in young people.

EMA assessments

Similar to an EMA study in schizophrenia [55] at each assessment (beep) participants rated their mood (negative (NA) and positive (PA) affect), then selected their current activity from categories and rated their enjoyment. They then selected current company from a selection of categories and rated their enjoyment. Next, they selected their future activity from the same categories and rated their anticipatory pleasure, expectation (likelihood of activity happening) and motivation (interest and preference). They then selected future company from categories and rated their anticipatory pleasure. The motivation questions were posed indirectly so as not to intervene or influence, this style of questioning limits the potential for the participant to change their behaviour in response to the question [55] (Table 1).

Table 1. EMA Questionnaire.

Reward Sub-process	Questions	Categories and Ratings
Mood	"Right now, I feel…"	Cheerful, Ashamed, Annoyed, Enthusiastic, Relaxed, Anxious, Satisfied, Lonely, Insecure, Down, Guilty. 1 not at all- 7 very much
Current Physical	What were you doing just before the beep went off? *(select one)*	Relaxing, Work/School, Studying, Chores, Shopping, Hygiene, Eating/Drinking, Travelling, Social Media, Exercising, Other Leisure Activity, Nothing.
Enjoyment	How much are you enjoying this activity?	1 not at all- 7 very much
Current Company	Who are you with? *(select one)*	Partner, Friends, Family, Colleagues, Acquaintances, Strangers, Nobody.
Enjoyment	How much are you enjoying being in this company?	1 not at all- 7 very much
Future Physical	What activity will you be doing after this one? *(select one)*	Relaxing, Work/School, Studying, Chores, Shopping, Hygiene, Eating/Drinking, Travelling, Social Media, Exercising, Other Leisure Activity, Nothing.
Anticipatory Pleasure	How much do you think you will enjoy this activity?	1 not at all- 7 very much
Interest	How interested are you in this activity?	1 not at all- 7 very much
Preference	Would you prefer to do something else?	1 not at all- 7 very much
Expectation	What do you think are the chances this activity will occur?	Rated from 0 to 100%.
Future Company	Who will you be with? *(select one)*	Partner, Friends, Family, Colleagues, Acquaintances, Strangers, Nobody.
Anticipatory Pleasure	How much do you think you will enjoy this company?	1 not at all- 7 very much

Table 1 caption: Description of the EMA questionnaires, showing the questions used to capture the reward sub-processes and categories of activities and company, and how they were rated.

Procedure

The experimenter met with each participant to brief them on the app. Participants were then required to log on and fill in their age, gender, ethnicity and the MFQ. EMA assessments began the next day. Participants were asked to respond to each assessment as soon as possible, otherwise they would expire.

We collected data 7 times a day, between 8:30am and 10pm, for 6 days, during the period July 2022 to Oct 2023. There was at least 45 min delay between each semi-random assessment which took approx. 1 min to complete and expired after 20 minutes. This sampling frequency and questionnaire design has been shown to encourage compliance and reduce burden in young people and those with mood disorders [58, 59, 62, 63]. We contacted participants on days 2 and 5 to check that they were receiving notifications and to troubleshoot any problems.

At the end of the study, we collected app user experiences (Table S2), and participants were debriefed and advised that if concerned about their mood to contact their GP or the mental health charity the Samaritans.

Data Analysis

Fisher's Exact tests, ANOVAs and Chi-square (χ2) statistics were used to examine group differences in the demographic data. We prepared the EMA data using *esmpack* in R [64]. Activity and company enjoyment and engagement were calculated across participants and ranked from highest to lowest. To check for potential confounds we ran multilevel regression models using lme4 package in R with mood (NA and PA), assessment time (1-7) and assessment day (1-6) as predictors of anticipation, motivation and enjoyment. Predictors were subject-mean centred and represented at Level 1 and symptoms were Level 2 fixed effects. All multilevel models were represented by a subject-level random intercept. As assessment time and mood covaried they were added to all multi-level analyses as covariates (Table S3).

We next ran multilevel models with depression as a continuous variable (MFQ) as a predictor of anticipation, motivation and enjoyment across all activity, then specifically leisure (relaxing, other leisure and exercise) and functional activity (work/school, studying, chores, shopping, hygiene, eating/drinking, travelling). We also ran multilevel models with depression as a continuous variable as a predictor of anticipatory pleasure and enjoyment across all company, then specifically social (partner, friends, family) and non-social company (nobody). We then examined the effects of depression symptoms on enjoyment and engagement for each specific activity and specific company, using separate standard linear regression models.

The TEP cycle shows that anticipation and motivation are temporally predictive of enjoyment and engagement in activities [28, 29]. This is the basis of our theoretical framework (Figure S1), for examining the temporal dynamics using time-lagged analyses. Using anticipation and motivation as predictors at (t-1), we modelled activity enjoyment and engagement (0 = functional, 1 = leisure) as outcomes at (t) using multilevel linear and logistic models, respectively. Similarly, using anticipation at (t-1), we modelled company enjoyment and engagement (0 = non-social, 1 = social) as outcomes at (t). We reported data for the whole sample (WS) and participants by depression symptom severity; controls (C, ≤16 score on MFQ), moderate (MD, >16 and <27 MFQ) and high depression symptoms (HD, ≥27 MFQ). Splitting the sample into groups, similar to Li et al., 2019, allows us to compare the four main predictors (anticipatory pleasure, interest, preference, expectation) in the same model while controlling for each other, across each of the four groups.

As participants may anticipate doing something but then do something else, we also examined the data when the predictors (anticipation and motivation) and outcomes (enjoyment and engagement) were matched for the same events, e.g., anticipatory pleasure for exercise predicting enjoyment of exercise. However, matched data can mean much fewer assessments and possible model overparameterisation.

Results

2426 questionnaires were collected from 95 participants. We excluded participants who had <30% threshold of assessments (N=15) [65, 66], the mean compliance rate was 69%, similar to previous EMA studies [67]. 1.5% of assessments were incomplete and therefore removed from analysis.

Demographics

The final sample consisted of 2316 questionnaires. Participants self-identified as White (78.8%), Black (5%), Asian (11%), Mixed (2.5%), and Other (2.5%). The depression groups differed on symptoms as expected but also for age and assessment period, but not for gender, ethnicity, compliance, or assessment delay (Table 2).

Table 2. Demographics.

Characteristics	Whole Sample (n = 80, 2316)	C (n = 22, 610)	MD (n = 16, 439)	HD (n = 42, 1267)	Statistic	p
Age (years)	20.12 (2.3)	21.55 (2.79)	19.81 (2.04)	19.5 (1.77)	F(2,77) = 6.77	.002
Gender (% Male)	27.5	27.3%	31.2%	26.2%	Fisher's, two-tailed	.971
Gender Split (F/M/O)	57/22/1	16/6/0	11/5/0	30/11/1		
Compliance (%)	68.9 (16.43)	66 (15.61)	65.3 (18.21)	71.8 (15.99)	F(2,77) = 1.39	.255
Assessment Delay (mins.)	118 (41.05)	120 (42.67)	116 (40.83)	118 (40.38)	F(2,1559) = 0.68	.508
Assessment Period						
Holiday	879	370	197	312	$X^2(2) = 238.01$	<.001
Term-time	1437	240	242	955		
Ethnicity, n (%)	White = 63 (78.8)	White = 19 (86.3)	White = 13 (81.3)	White = 31 (73.8)	Fisher's, two-tailed	.816
	Black = 4 (5)	Black = 0 (0)	Black = 1 (6.3)	Black = 3 (7.1)		
	Asian = 9 (11)	Asian = 2 (9.1)	Asian = 1 (6.3)	Asian = 6 (14.3)		
	Mixed = 2 (2.5)	Mixed = 0 (0)	Mixed = 1 (6.3)	Mixed = 1 (2.4)		
	Other = 2 (2.5)	Other = 1 (4.5)	Other = 0 (0)	Other = 1 (2.4)		
MFQ	25.64 (13.1)	8.86 (3.67)	21 (3.04)	36.2 (6.83)	F(2,77) = 185.34	<.001
Medication for Depression	8/80	0	0	8	-	-

N= sample size, no of assessments. Mean (SD) unless stated otherwise. Holiday dates: <18yrs = 21-July-22 to 6-Sept-22, and 21-July to 26-Sept-22, >18 yrs. = 19-Dec-22 to 3-Jan-23. Any other dates =Term-time. MFQ, Mood and Feelings Questionnaire.

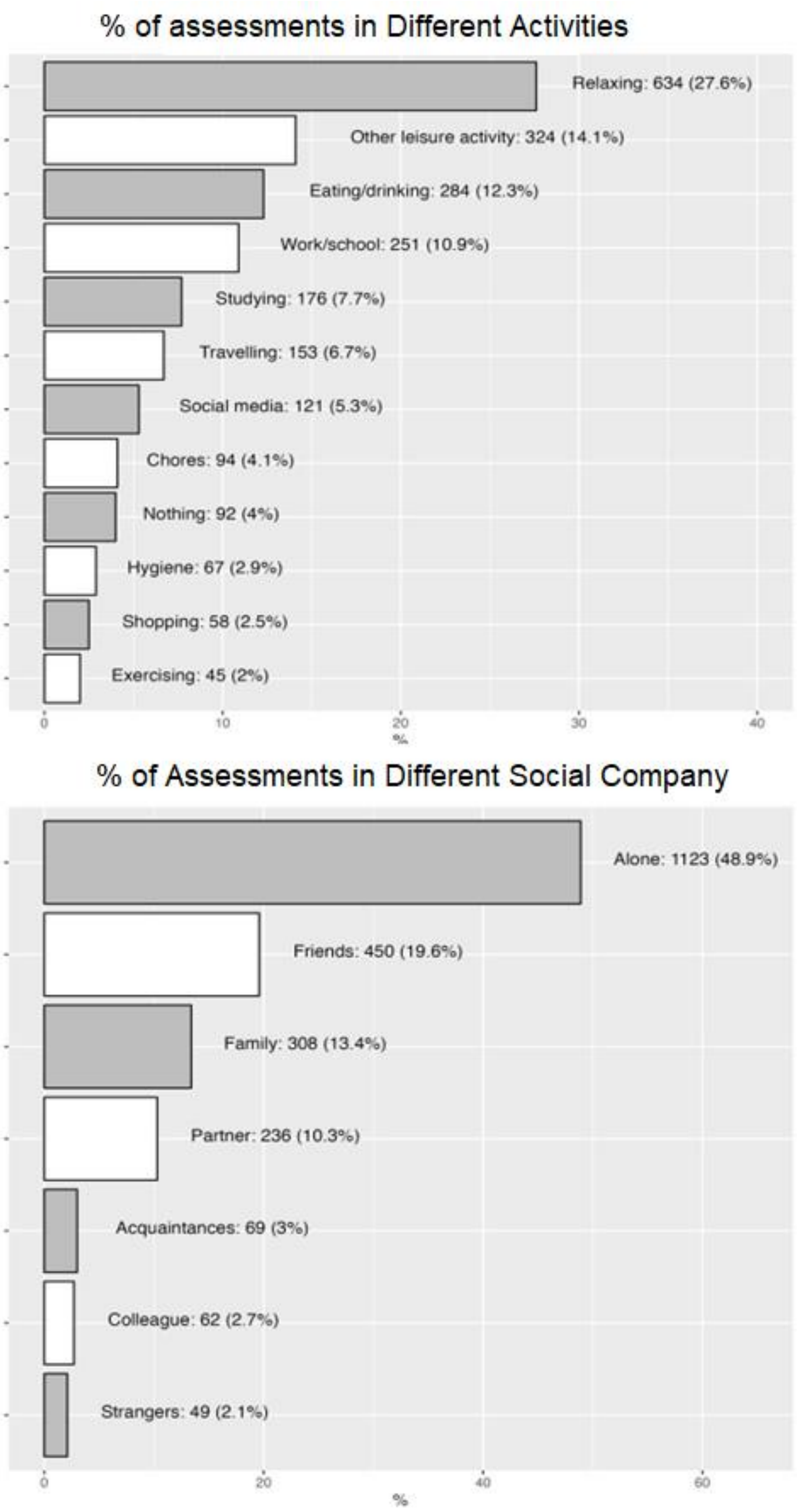
Table 2 caption: Description of demographics of the whole sample and the three groups: controls, moderate depression and high depression groups.

What activity do young people enjoy and engage with?

The leisure activities “exercising”, “relaxing”, “other leisure” were rated most enjoyable (Table S4). Young people engaged most frequently in “relaxing” and “other leisure” activities, followed by “eating/drinking” then “work/school” and “studying” (Figure 1).

What company do young people enjoy and engage with?

Being with “friends”, “family” and/or “partner” was rated highest for enjoyment (Table S5). Although young people spent more time alone than with others, they were mostly with “friends”, “family” and/or “partner” when socialising (Figure 1).



Caption for Figure 1. Activities and social company that young people engaged in.

Dimensional Analyses

Are depression symptoms associated with reduced anticipation, motivation and enjoyment of activity?

As depression increased, anticipation (anticipatory pleasure, expectation), motivation (interest, preference) and enjoyment decreased across all activities (Table S6). When examining data for leisure and functional activity, enjoyment and expectation also decreased as depression increased (Table S7).

Are depression symptoms associated with anticipation and enjoyment of company?

As depression increased anticipatory pleasure and enjoyment decreased across all company (Table S8). Anticipatory pleasure and enjoyment of social company (friends, family, partner) and enjoyment of non-social company (nobody) decreased as depression increased (Table S9).

Are depression symptoms associated with enjoyment and engagement in specific activities and specific company?

As depression increased enjoyment for “studying”, “eating/drinking” and “other leisure” activities decreased (Table S10) and as depression increased young people reported doing more “nothing”, less “work/school” and “hygiene” (Table S11). Depression did not predict enjoyment or engagement with any specific company.

Categorical analyses

Time-lagged analyses:

Predicting activity enjoyment and company enjoyment

Using multilevel time-lagged linear regressions anticipatory pleasure positively predicted enjoyment across all activity categories in the whole sample (WS), controls and in those with high depression symptoms (HD) (Table 3a). Expectation negatively predicted enjoyment across all activity categories in WS and HD (Table 3a).

Anticipatory pleasure positively predicted enjoyment across all company categories in all groups (Table 3b). Results were similar when predictors and outcomes were matched for the same events (Table S12).

Table 3. Reward predictors of activity enjoyment and company enjoyment

Table 3a Enjoyment of Activity

Predictors (t-1)	Whole Sample (n = 1514) β	95% CI	p	C (n = 389) β	95% CI	p	MD (n = 275) β	95% CI	p	HD (n = 850) β	95% CI	p
(Intercept)	4.426	4.189 to 4.663	<.001	4.677	4.291 to 5.063	<.001	4.313	3.741 to 4.885	<.001	4.290	3.965 to 4.615	<.001
Anticipatory Pleasure	0.118	0.051 to 0.185	<.001	0.160	0.019 to 0.301	.026	0.082	-0.089 to 0.253	.344	0.118	0.034 to 0.202	.006
Expectation	-0.006	-0.01 to -0.002	.001	-0.008	-0.016 to 0	.076	0.000	-0.008 to 0.008	.993	-0.008	-0.012 to -0.004	.001
Motivation (Interest)	0.057	-0.006 to 0.12	.076	0.000	-0.137 to 0.137	.995	0.104	-0.051 to 0.259	.189	0.051	-0.029 to 0.131	.22
Motivation (Prefer)	0.027	-0.016 to 0.07	.214	0.016	-0.062 to 0.094	.696	-0.034	-0.138 to 0.07	.519	0.056	-0.003 to 0.115	.058

Table 3b Enjoyment of Company

Predictors (t-1)	Whole Sample (n = 1516) β	95% CI	p	C (n = 389) β	95% CI	p	MD (n = 277) β	95% CI	p	HD (n = 850) β	95% CI	p
(Intercept)	5.230	5.038 to 5.422	<.001	5.585	5.23 to 5.94	<.001	5.482	5.055 to 5.909	<.001	4.952	4.705 to 5.199	<.001
Anticipatory Pleasure	0.329	0.278 to 0.38	<.001	0.342	0.246 to 0.438	<.001	0.244	0.119 to 0.369	<.001	0.341	0.272 to 0.41	<.001

Time-lagged Linear regressions, n= number of assessments. Controlled for assessment time, and mood (NA and PA). When age and assessment period added as extra covariates results remain the same.

Table 3 caption: Time-lagged predictors of enjoyment of a) activities and b) company, in the whole sample, controls, moderate depression and high depression groups.

Predicting leisure enjoyment and social company enjoyment

When looking specifically at leisure (exercising, relaxing and other leisure activity) we found motivation (interest) positively predicted leisure enjoyment at trend in the WS (*P*=.06) (Table S13a). Anticipatory pleasure positively predicted enjoyment of social company (friends, family, partner) in both the WS and HD groups and at trend in the MD group (*P*=.055) (Table S13b).

Predicting leisure engagement and social company engagement

Using multilevel time-lagged logistic regressions, anticipatory pleasure and motivation (preference) positively predicted engagement in leisure in the WS and controls (Table 4a). When predictors and outcomes were matched for the same leisure events, anticipatory pleasure positively predicted engagement in leisure activities in the WS and HD group (Table S14a). Expectation negatively predicted engagement in leisure in the WS, controls and HD groups (Table 4a).

Anticipatory pleasure positively predicted engagement in social company in the WS and controls and in the matched condition (when predictors and outcomes were for the same social company) (Table 4b and S14 b). Anticipatory pleasure did not predict engagement in social company in the MD or HD groups.

Table 4. Reward predictors of leisure activity engagement and social company engagement.

Table 4a Leisure vs. Functional Activity Engagement

	Whole Sample (n = 1383)			C (n = 365)			MD (n = 257)			HD (n = 761)		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	-0.633	-0.943 to -0.323	<.001	-0.514	-1.161 to 0.133	.12	-0.973	-1.688 to -0.258	.008	-0.620	-1.032 to -0.208	.003
Anticipatory Pleasure	0.194	0.069 to 0.319	.003	0.426	0.13 to 0.722	.005	0.232	-0.105 to 0.569	.177	0.129	-0.028 to 0.286	.105
Expectation	-0.014	-0.022 to -0.006	<.001	-0.032	-0.05 to -0.014	.001	-0.005	-0.021 to 0.011	.551	-0.013	-0.021 to -0.005	.003
Motivation (Interest)	-0.056	-0.176 to 0.064	.354	-0.142	-0.422 to 0.138	.324	0.006	-0.29 to 0.302	.967	-0.079	-0.228 to 0.07	.299
Motivation (Prefer)	0.105	0.023 to 0.187	.011	0.165	0.002 to 0.328	.048	0.090	-0.116 to 0.296	.388	0.087	-0.023 to 0.197	.118

Table 4b Social vs. Non-Social Company Engagement

	Whole Sample (n = 1413)			C (n = 361)			MD (n = 270)			HD (n = 782)		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	-0.046	-0.279 to 0.187	.703	-0.056	-0.556 to 0.444	.825	-0.024	-0.406 to 0.358	.902	-0.053	-0.392 to 0.286	.760
Anticipatory Pleasure	0.095	0.001 to 0.189	.047	0.343	0.116 to 0.57	.003	0.068	-0.177 to 0.313	.583	0.033	-0.083 to 0.149	.570

Time-Lagged Logistic regressions, n= number of assessments. Outcomes coded as 1 and 0, respectively. Controlled for assessment time, and mood (NA and PA). When age and assessment period added as extra covariates results remain the same.

Table 4 caption: Time-lagged predictors of engagement in a) leisure activities and b) social company, in the whole sample, controls, moderate depression and high depression groups.

Discussion

Principal Results

To our knowledge, this is the first study to demonstrate in real-world settings that anticipatory pleasure reliably predicts future enjoyment across various physical activities and social contexts, in young people. While anticipatory pleasure predicts leisure and social engagement in the overall sample, this relationship is absent in individuals with higher depression symptoms. However, when measured for the same specific event, anticipatory pleasure does predict leisure engagement in those with higher depression symptoms, indicating a potential target for intervention.

Comparison with Prior Work

While prior research has established that depression blunts reward-related processes [31], most studies rely on retrospective reports or laboratory tasks that fail to capture the temporal dynamics of reward processing in daily life. By leveraging ecological momentary assessment (EMA), this study provides novel insights into how anticipation and motivation dynamically shape behaviour in real-world contexts. Consistent with prior work [57, 68], we found that individuals with higher depression symptoms reported less enjoyment across various activities. However, our study extends these findings by showing that depression is also linked to a broader dampening of anticipation and motivation across functional, leisure and social experiences. This supports the idea that depression is not only associated with reduced momentary pleasure but also with a diminished ability to anticipate and seek out rewarding experiences.

Our study also provides a nuanced perspective on real-world activity deficits in depression. Individuals with higher depression symptoms reported lower enjoyment in activities such as studying, eating/drinking, and other leisure activities, as well as reduced engagement in work/school and hygiene. Importantly, depression was associated with doing more "nothing," a behavioural pattern consistent with wearable-monitor studies showing reduced activity in depression [69, 70]. However, our results go beyond previous findings by contextualizing these activity deficits within specific daily-life behaviours. The reduction in work/school and hygiene aligns with known risk factors for depression, such as academic underachievement [71] and self-neglect [72]. These findings suggest that ecological momentary interventions (EMIs) could be developed to support goal-setting, progress tracking, and real-time encouragement for maintaining daily routines [48, 73].

Crucially, we demonstrate for the first time that anticipatory pleasure significantly predicts future enjoyment across all physical activities and social contexts. Anticipatory pleasure and motivation (preference) predicted leisure engagement and anticipatory pleasure predicted social engagement in the whole sample and controls but not in individuals with depression symptoms. However, anticipatory pleasure did predict leisure engagement in those with high depression symptoms, when assessed for the same specific event. This suggests that while individuals with depression may struggle to generalize anticipation across contexts, if they can be encouraged to anticipate specific leisure activities, they may be more likely to engage in them, which could strengthen the anticipation-engagement link over time.

Our findings support the development of interventions that could exploit the time-lagged relationships such as Episodic Future Thinking (EFT) [74], a cognitive exercise that uses mental imagery to anticipate the feelings associated with future positive activities. Preliminary data suggests EFT can increase anticipatory pleasure using both traditional scales [75-77] and EMA [78] in healthy controls and MDD. Therefore, we propose an EFT-based EMI could be developed and tested to see if it could increase engagement in leisure and social activities in young people with depression symptoms.

A striking finding was that higher expectation (likelihood of activity happening) was associated with lower enjoyment, especially in those with high depression symptoms. This aligns with our finding that the least enjoyable activities were work/school and studying, activities that are usually scheduled and therefore highly expected. Consistent with this, we found enjoyment for activities such as studying decreased as depression increased and that higher expectation predicted more engagement with functional vs leisure activities, across groups. These findings are supported by previous reports that show activity scheduling reduces enjoyment, potentially due to diminished spontaneity [79].

Our findings could be explained by Self-Determination Theory (SDT) [80], whereby activities that are externally imposed (like school/studying) and extrinsically motivated (to pass exams) tend to be less enjoyable, especially if autonomy is low, contrasted with activities that are intrinsically motivated like leisure (inherently enjoyable). In depressed individuals, the lack of intrinsic reward and reduced agency may amplify the negative experience of expected, scheduled tasks. As the least enjoyable activities in this study are the ones most likely scheduled—this aligns with SDT's view that perceived autonomy is key to enjoyment and well-being. Moreover, as individuals with depression tend to hold negative core beliefs and cognitive distortions [81] negative biases could lead to negative perceptions of predictable activities, like school/work, sustaining low enjoyment.

Taken together, highly expected activities are often externally imposed, reducing autonomy and intrinsic motivation. For youth with depression, these activities—especially when perceived as unpleasant—could confirm negative schemas about being powerless or trapped [81], which could lead to lower enjoyment and possibly deeper anhedonia. Future research should explore whether EMIs that promote spontaneous enjoyable activities, while addressing negative cognitive biases, could enhance activity engagement in depression.

Limitations

While our study offers significant contributions, several limitations must be acknowledged. First, although EMA captures real-time experiences, self-report measures remain subject to bias. Future studies could integrate passive sensing data (e.g., activity trackers, voice recordings) to objectively assess engagement [82]. Second, our sample consisted of young adults, limiting generalizability to older populations. In future studies, time-lagged relationships should be investigated in a broader demographic. Third, while we demonstrated the predictive role of anticipation and motivation, causality remains uncertain. Experimental studies using reward-training interventions could further elucidate these mechanisms.

Conclusions

Our results support anticipation and intrinsic motivation as novel intervention targets for real-time, technology-driven approaches to managing depression. By leveraging digital tools to enhance anticipation and motivation, future interventions could empower individuals to engage with rewarding experiences, ultimately improving mental health outcomes.

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Conflicts of interests:
The authors report no conflicts of interest.

Abbreviations:
EMA: Ecological momentary Assessments
MFQ: Mood and Feelings Questionnaire
NA: Negative affect
PA: Positive affect
HD: High depression
MD: Moderate depression
C: Controls
BA: Behavioural Activation

Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supplementary information

Time-lagged Analyses:

Table S14. Reward predictors of leisure engagement and social company engagement, when predictors and outcomes are for the same events.

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2.2. Supplemental Online Content

Sahni A & McCabe C, **Anticipation and Motivation as predictors of Leisure and Social Enjoyment and Engagement in Young People with Depression Symptoms: An Ecological Momentary Assessment Study.**
Supplementary

This supplemental material has been provided by the authors to give readers additional information.

Figure S1. Visual Model of the Theoretical Framework.

Adapted from the Temporal Experience of Pleasure (TEP) cycle by Kring and Barch [1], the visual model of the theoretical framework of the time-lagged models is shown in Figure S1. The models examine how anticipation (anticipatory pleasure, expectation) and motivation (interest, preference) (at t-1) predict enjoyment and engagement (at t) in leisure and social activities.

The TEP cycle demonstrates that, after experiencing enjoyment, the subjective pleasure associated with an activity is updated. The next time the same activity is anticipated, the updated subjective pleasure is reflected in its anticipatory pleasure.

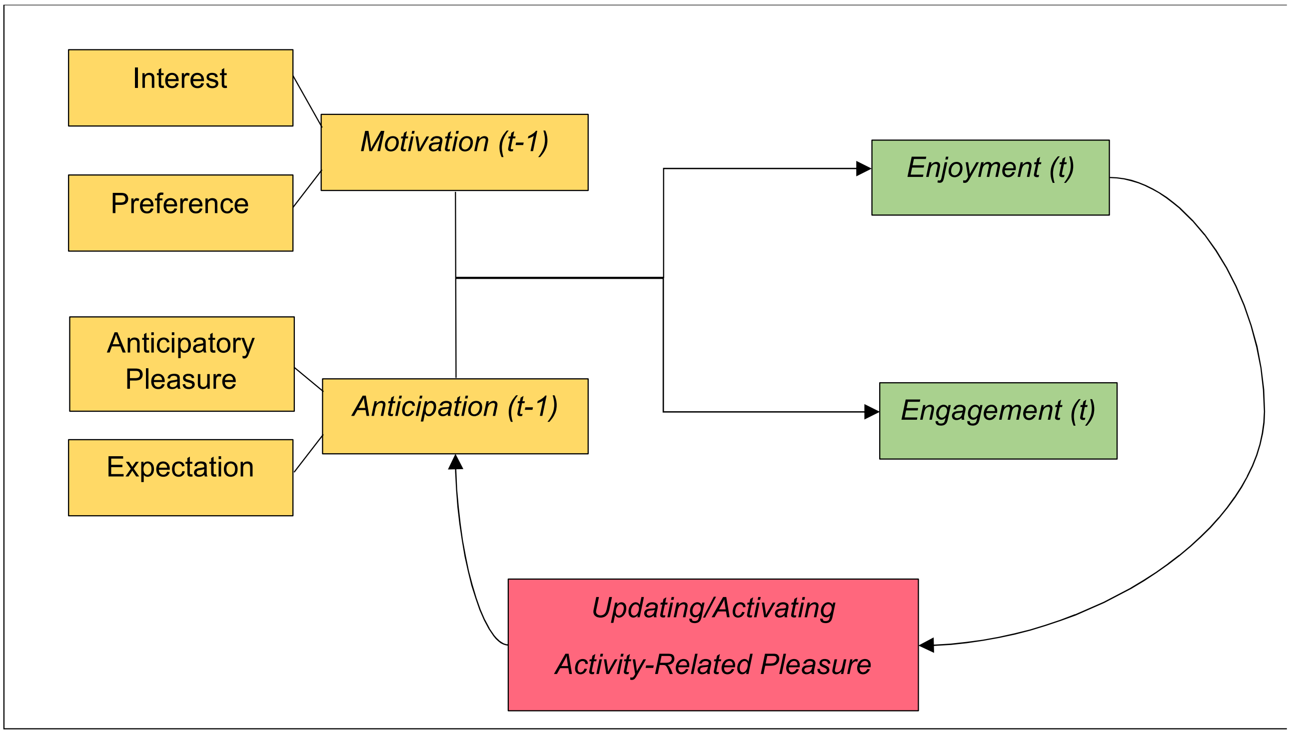


Figure S1. The theoretical framework of the time-lagged models, adapted from the temporal experience of pleasure (TEP) cycle by Kring and Barch [1].

Power analysis

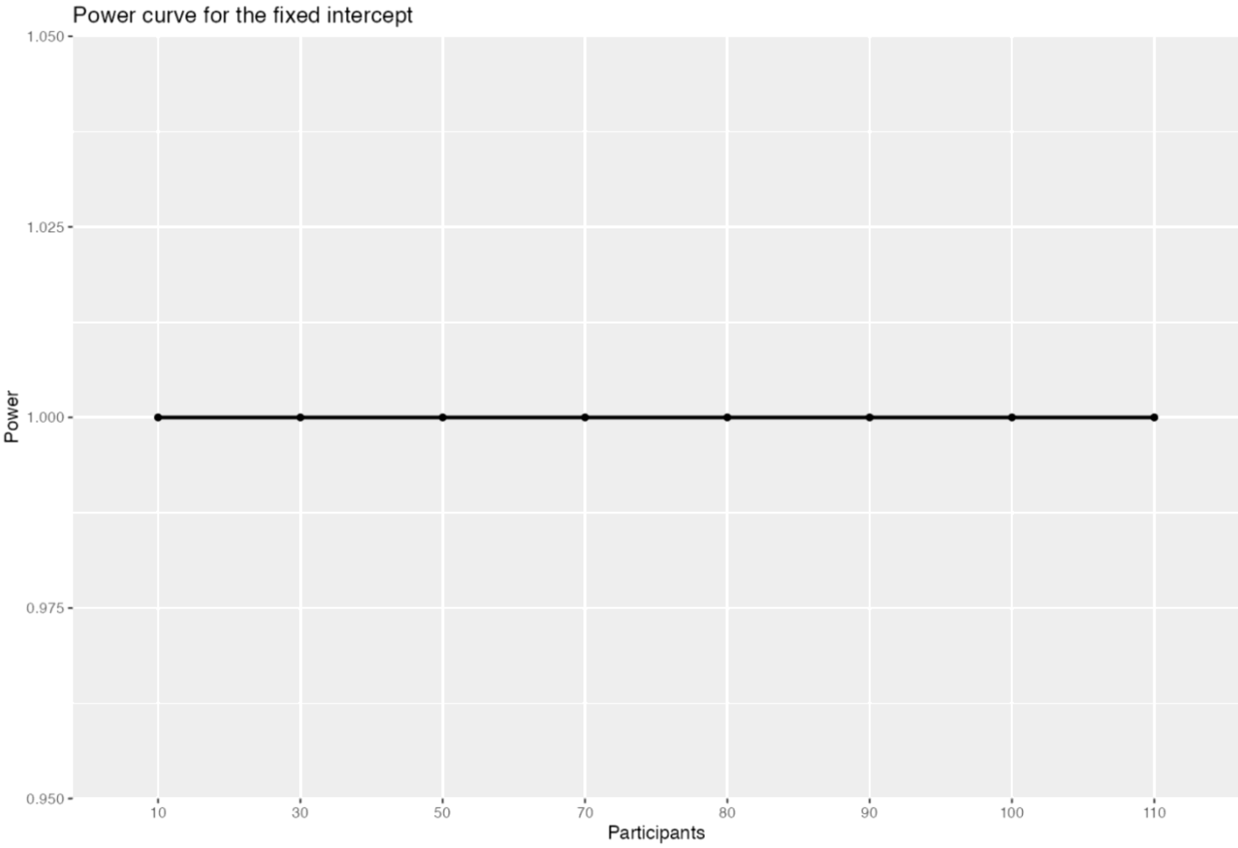
Power calculations for EMA studies are complicated due to the intensive longitudinal study designs and are thus rarely reported. Using a recently developed app specifically designed for EMA power analysis PowerAnalysisIL [2] we conducted an *a priori* power analysis. We requested data from Li et al., as they also examined the relationship between depression symptoms and reward processes in an EMA study in young people (N=100) [3]. We utilised Model 2 in the app where Level 2 is represented by a subject-level random intercept and the Level 2 predictor (depression score) predicts anticipatory pleasure [2]. At 1000 Monte Carlo replicates, the relevant parameters (Table S1) extracted from their data created a power curve for the effect of the Level 2 variable (effect of interest in our study in Table S8 – depression predicting EMA measures). This analysis suggested that 80% power could be achieved with a sample size of 50 (Figure S2). Consistent with this estimates from multilevel logistic [4] and linear models [5] also suggest a minimum sample size of 50 for our design.

Table S1. Parameters extracted from Li et al. study data.

Table S1

Parameters	**Notation**	**Model Estimate**
Time points		44 (max = 56); 79% mean compliance.
Mean of Level 2 continuous variable (BDI Total)	μ_W	16.08
Std. Dev. of BDI Total	σ_W	9.58
Fixed Intercept	β_{00}	7.31
Effect of BDI Total (level 2) on Level 1 Intercept	β_{01}	-0.049
Std. Dev. of Level 1 error (residuals)	σ_ε	1.60
Autocorrelation of Level 1 error	ρ_ε	0.15
Std. Dev. of Random Intercept (subject level)	σ_{v0}	1.09

Figure S2. Power curves generated in the app, PowerAnalysisIL.



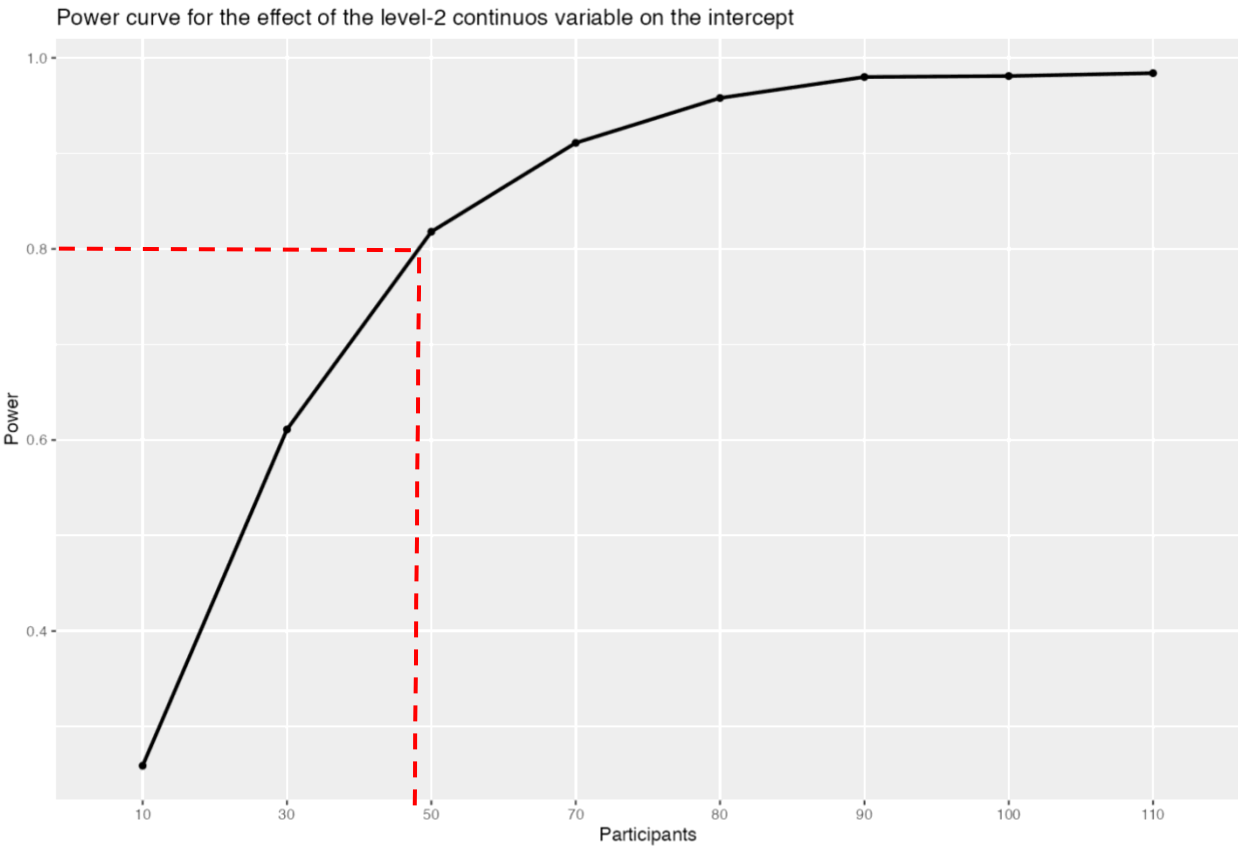


Table S2. App User Experience.

At the end of the study, 87% of responders reported that it was a normal week and that their mood, activities and contact with other people was not affected by using the app. Participants reported very few mistakes or technical issues. There were no group differences on any of the app user measures (Table S3).

Questions	**Options**	**Whole Sample (N=68)**	**C (N=18)**	**MD (N=15)**	**HD (N=35)**	**Statistic**	**p**
Do you feel this has been a normal week for you?	Yes/No	59/9	15/3	14/1	30/5	*Fisher's Exact*	.803
Did the participation in the PsyMate study affect your mood?	1=worsened, 4=no affect, 7=increased	3.75 (0.74)	3.67 (0.59)	3.67 (0.72)	3.83 (0.82)	H(2, 68) = 0.62	.734
Did the participation in the PsyMate study affect your activities?	1=decreased, 4=no affect, 7=increased	4.1 (0.63)	4.17 (0.62)	4.13 (0.35)	4.06 (0.73)	H(2, 68) = 1.43	.489
Did the participation in the PsyMate study affect your contacts with other people?	1=decreased, 4=no affect, 7=increased	3.9 (0.49)	4.06 (0.54)	3.87 (0.52)	3.83 (0.45)	H(2, 68) = 2.14	.343
Did you make any mistakes answering the questions?	1=none, 4=few, 7=many	2.66 (1.25)	2.44 (1.54)	2.73 (1.22)	2.74 (1.12)	H(2, 68) = 1.55	.461
Did you have technical difficulties using the PsyMate?	1=not at all, 4=moderately, 7=very much	2.47 (1.97)	2.25 (1.34)	3 (2)	1.97 (1.52)	H(2, 68) = 3.56	.169

Mean (SD). Response rate was 68/80 (85%). Kruskal-Wallis test comparing between groups unless stated otherwise.

Table S3. Covariates Mood (PA and NA) and Assessment time predict Anticipation, Motivation and Enjoyment.

Table S3		**PA**			**NA**			**Assessment time**		
	Sub-processes	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
Activity	Anticipation	0.11	0.1 to 0.12	<.001	-0.06	-0.08 to -0.05	<.001	0.10	0.08 to 0.12	<.001
	Expectation	0.49	0.3 to 0.68	<.001	-0.38	-0.53 to -0.23	<.001	-0.03	-0.4 to 0.34	.90
	Motivation (Interest)	0.09	0.08 to 0.11	<.001	-0.05	-0.06 to -0.04	<.001	0.07	0.03 to 0.11	<.001
	Motivation (Prefer)	0.12	0.1 to 0.14	<.001	-0.07	-0.09 to -0.06	<.001	0.12	0.08 to 0.16	<.001
	Enjoyment	0.19	0.18 to 0.2	<.001	-0.09	-0.1 to -0.08	<.001	0.05	0.01 to 0.09	<.001
Social	Anticipation	0.09	0.08 to 0.11	<.001	-0.07	-0.08 to -0.06	<.001	0.06	0.04 to 0.08	<.001
	Enjoyment	0.13	0.11 to 0.14	<.001	-0.09	-0.1 to -0.08	<.001	0.03	0.01 to 0.05	.02

Table S4. Ranking of Activity by Enjoyment.

Rank	Mean Enjoyment (SD)	Activity	Assessments
1	5.42 (1.41)	Exercising	45
2	5.25 (1.35)	Relaxing	634
3	5.22 (1.38)	Other leisure activity	324
4	5.11 (1.43)	Eating/drinking	284
5	4.93 (1.09)	Shopping	58
6	4.46 (1.27)	Hygiene	67
7	4.43 (1.42)	Social media	121
8	4.06 (1.39)	Travelling	153
9	3.77 (1.23)	Chores	94
10	3.55 (1.58)	Nothing	92
11	3.52 (1.49)	Studying	176
12	3.46 (1.49)	Work/school	251

Table S5. Ranking of Company by Enjoyment.

Rank	Mean Enjoyment (SD)	Company	Assessments
1	6.17 (1.42)	Partner	236
2	5.82 (1.16)	Friends	450
3	5.44 (1.37)	Family	308
4	4.88 (1.57)	Nobody	1,123
5	4.74 (1.05)	Colleague	62
6	4.26 (1.15)	Acquaintances	69
7	3.51 (1.32)	Strangers	49

Table S6. Depression as a predictor of activity anticipation, motivation and enjoyment.

Table S6

	Sub-processes	**β**	**95% CI**	**p**
Activity	Anticipatory Pleasure	-0.019	-0.033 to -0.005	0.008
	Expectation	-0.265	-0.502 to -0.028	0.031
	Motivation (Interest)	-0.015	-0.028 to -0.002	0.026
	Motivation (Prefer)	-0.019	-0.033 to -0.005	0.010
	Enjoyment	-0.016	-0.028 to -0.004	0.009

Multilevel linear models with MFQ as predictor. Controlled for assessment time, and mood (NA and PA).

Table S7. Depression predicting anticipation, motivation and enjoyment of leisure and functional activity.

Table S7

	Leisure			**Functional**		
Sub-processes	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
Anticipatory Pleasure	-0.013	-0.026 to 0.001	0.076	-0.014	-0.029 to 0.001	0.068
Expectation	-0.288	-0.543 to -0.034	0.029	-0.245	-0.484 to -0.006	0.048
Motivation (Interest)	-0.013	-0.027 to 0.001	0.071	-0.009	-0.024 to 0.005	0.203
Motivation (Prefer)	-0.014	-0.029 to 0.001	0.070	-0.012	-0.029 to 0.005	0.175
Enjoyment	-0.019	-0.033 to -0.005	0.011	-0.012	-0.024 to 0	0.048

Multilevel linear models with MFQ as predictor. Controlled for assessment time, and mood (NA and PA). Leisure (exercise, relaxing and other leisure) functional (work/school, studying, chores, shopping, hygiene, eating/drinking, travelling).

Table S8. Depression as a predictor of company enjoyment.

Table S8

	Sub-processes	**β**	**95% CI**	**p**
Company	Anticipatory Pleasure	-0.017	-0.033 to -0.002	0.033
	Enjoyment	-0.019	-0.033 to -0.004	0.012

Multilevel linear models with MFQ as predictor. Controlled for assessment time, and mood (NA and PA).

Table S9. Depression as a predictor of anticipation and enjoyment of social and non-social company.

Table S9

	Social			**Non-Social**		
Sub-processes	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
Anticipatory Pleasure	-0.027	-0.042 to -0.012	0.001	-0.017	-0.037 to 0.004	0.120
Enjoyment	-0.020	-0.036 to -0.005	0.013	-0.023	-0.043 to -0.004	0.023

Multilevel linear models with MFQ as predictor. Controlled for assessment time, and mood (NA and PA). Social (Friends, family, partner) Non-social (nobody).

Table S10. Depression as a predictor of specific activity and company enjoyment.

Table S10

		β	95% CI	p
Activity	Relaxing	-0.010	-0.026 to 0.005	.207
	Work/school	-0.014	-0.032 to 0.005	.159
	Studying	-0.032	-0.05 to -0.013	.005
	Chores	-0.019	-0.046 to 0.006	.164
	Shopping	0.003	-0.021 to 0.026	.831
	Hygiene	0.009	-0.02 to 0.039	.534
	Eating/drinking	-0.022	-0.04 to -0.004	.022
	Travelling	-0.018	-0.041 to 0.005	.130
	Social media	-0.021	-0.05 to 0.007	.152
	Exercising	-0.003	-0.044 to 0.04	.907
	Other leisure activity	-0.020	-0.036 to -0.004	.018
	Nothing	-0.018	-0.053 to 0.018	.330
Company	Partner	-0.009	-0.039 to 0.02	.537
	Friends	-0.013	-0.033 to 0.007	.207
	Family	-0.018	-0.044 to 0.008	.189
	Colleague	0.003	-0.019 to 0.026	.774
	Acquaintances	0.003	-0.025 to 0.031	.825
	Strangers	0.026	-0.021 to 0.075	.293
	Nobody	-0.017	-0.037 to 0.003	.101

Multilevel linear models with MFQ as a predictor of Enjoyment. Controlled for assessment time, and mood (NA and PA).

Table S11. Depression as a predictor of specific activity and company engagement.

Table S11

		β	95% CI	p
Activity	Relaxing	-0.084	-0.333 to 0.165	0.511
	Work/school	-0.256	-0.458 to -0.054	0.016
	Studying	-0.180	-0.39 to 0.03	0.098
	Chores	-0.065	-0.243 to 0.113	0.478
	Shopping	0.030	-0.035 to 0.095	0.366
	Hygiene	-0.088	-0.166 to -0.01	0.033
	Eating/drinking	0.078	-0.051 to 0.207	0.241
	Travelling	0.003	-0.115 to 0.121	0.954
	Social media	0.054	-0.095 to 0.203	0.481
	Exercising	-0.041	-0.127 to 0.045	0.356
	Other leisure activity	-0.033	-0.227 to 0.161	0.740
	Nothing	0.170	0.027 to 0.313	0.026
Company	Partner	-0.341	-0.721 to 0.039	0.086
	Friends	0.002	-0.357 to 0.361	0.993
	Family	0.053	-0.296 to 0.402	0.766
	Colleague	-0.165	-0.465 to 0.135	0.294
	Acquaintances	0.204	-0.108 to 0.516	0.208
	Strangers	-0.031	-0.315 to 0.253	0.831
	Nobody	-0.067	-0.414 to 0.28	0.707

Multilevel linear models with MFQ as a predictor of Engagement. Controlled for assessment time, and mood (NA and PA). Engagement was calculated as the % of a subject’s total assessments spent in each activity.

Time-lagged analyses:

Table S12. Reward predictors of activity enjoyment and company enjoyment, when predictors and outcomes are for the same events.

Table 12a Activity Enjoyment

	Whole Sample (n = 106)			**C (n = 22)**			**MD (n = 19)**			**HD (n = 65)**		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	4.733	3.808 to 5.658	<.001	5.694	3.132 to 8.256	.001	5.222	2.684 to 7.76	.003	4.231	3.041 to 5.421	<.001
Anticipatory Pleasure	0.648	0.44 to 0.856	<.001	0.134	-0.528 to 0.796	.697	0.741	-0.072 to 1.554	.112	0.723	0.476 to 0.97	<.001
Expectation	-0.007	-0.023 to 0.009	.376	0.010	-0.041 to 0.061	.704	0.004	-0.047 to 0.055	.884	-0.012	-0.03 to 0.006	0.182

Table 12b Company Enjoyment

	Whole Sample (n = 412)			**C (n = 102)**			**MD (n = 51)**			**HD (n = 259)**		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	5.241	4.996 to 5.486	<.001	5.555	5.094 to 6.016	<.001	5.588	5.086 to 6.09	<.001	4.971	4.64 to 5.302	<.001
Anticipatory Pleasure	0.660	0.562 to 0.758	<.001	0.686	0.474 to 0.898	<.001	0.603	0.344 to 0.862	<.001	0.661	0.538 to 0.784	<.001

Time-lagged linear regressions, predictors (t-1) and enjoyment (t) are matched for the same events e.g., relaxing to relaxing, friends to friends. Controlled for assessment time, and mood (NA and PA). When age and assessment period added as extra covariates, results remain the same.

Table S13. Reward predictors of leisure enjoyment and social company enjoyment.

Table S13a Leisure activity enjoyment

	Whole Sample (n = 325)			C (n = 111)			MD (n = 51)			HD (n = 163)		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	5.020	4.634 to 5.406	<.001	5.277	4.652 to 5.902	<.001	4.866	3.835 to 5.897	<.001	4.642	4.054 to 5.23	<.001
Anticipatory Pleasure	-0.060	-0.203 to 0.083	.408	0.008	-0.251 to 0.267	.949	-0.013	-0.478 to 0.452	.957	-0.071	-0.269 to 0.127	.483
Expectation	0.003	-0.005 to 0.011	.462	-0.007	-0.023 to 0.009	.354	-0.002	-0.02 to 0.016	.797	0.007	-0.005 to 0.019	.201
Motivation (Interest)	0.127	-0.006 to 0.26	.062	0.114	-0.123 to 0.351	.347	0.256	-0.069 to 0.581	.130	0.094	-0.1 to 0.288	.346
Motivation (Prefer)	0.047	-0.043 to 0.137	.308	0.047	-0.1 to 0.194	.532	0.003	-0.273 to 0.279	.982	0.045	-0.082 to 0.172	.492

Table S13b Social company enjoyment

	Whole Sample (n = 694)			C (n = 179)			MD (n = 133)			HD (n = 382)		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	5.735	5.529 to 5.941	<.001	6.186	5.963 to 6.409	<.001	5.860	5.437 to 6.283	<.001	5.471	5.165 to 5.777	<.001
Anticipatory Pleasure	0.188	0.127 to 0.249	<.001	0.076	-0.036 to 0.188	.181	0.155	-0.002 to 0.312	.055	0.223	0.145 to 0.301	<.001

Time-lagged linear regressions. Controlled for assessment time, and mood (NA and PA). When age and assessment period added as extra covariates, results remain the same.

Table S14. Reward predictors of leisure engagement and social company engagement, when predictors and outcomes are for the same events.

Table S14a Leisure activity engagement

	Whole Sample (n = 408)			**C (n = 122)**			**MD (n = 70)**			**HD (n = 216)**		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	5.509	5.135 to 5.883	<.001	6.163	5.681 to 6.645	<.001	5.437	4.496 to 6.378	<.001	5.183	4.613 to 5.753	<.001
Anticipatory Pleasure	0.182	0.088 to 0.276	<.001	0.034	-0.142 to 0.21	.703	0.137	-0.11 to 0.384	.284	0.222	0.091 to 0.353	.001

Table S14b Social company engagement

	Whole Sample (n = 396)			**C (n = 97)**			**MD (n = 51)**			**HD (n = 248)**		
Predictors (t-1)	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**	**β**	**95% CI**	**p**
(Intercept)	-0.512	-1.049 to 0.025	.061	-0.722	-2.127 to 0.683	.313	-0.641	-1.505 to 0.223	.146	-0.393	-1.112 to 0.326	.284
Anticipatory Pleasure	0.254	0.021 to 0.487	.033	0.855	0.151 to 1.559	.017	0.439	-0.394 to 1.272	.301	0.114	-0.149 to 0.377	.396

Time-lagged linear regressions, predictors (t-1) and engagement (t) are matched for the same events e.g., relaxing to relaxing, friends to friends. Controlled for assessment time, and mood (NA and PA). When age and assessment period added as extra covariates, results remain the same.

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3. Paper 2

The Mood Brightening effect of Leisure activities and Social company in Young People with Depression and Anhedonia Symptoms: An Ecological Momentary Assessment Study

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Abstract

It is thought that positive activities can increase positive affect (PA) and decrease negative affect (NA). A phenomenon described as the mood brightening (MB) effect suggests that these changes are enhanced in Major Depressive Disorder (MDD). However, what drives the MB effect of leisure activities and social company in the real-world remains unknown.

Methods

Participants (N=71, mean age = 20 years) used the Psymate2 smartphone app to report their current activity and social company from a list of options, 7 times a day for 6 days. These were categorised into leisure or functional activities, and social or non-social company. They also rated how cheerful, enthusiastic, relaxed, satisfied they felt on a 7-point Likert scale and the mean score was considered PA. They rated annoyed, anxious, ashamed, down and the mean score was considered NA. Depression symptoms were measured by the Mood and Feelings Questionnaire (MFQ) and Anhedonia by the Anhedonia Scale for Adolescents (ASA). We measured affective reactivity as the difference between PA and NA at the time of the activity engagement compared to the previous assessment (or t-1) and compared to the within-subject mean. Multilevel linear regression models examined the interaction of activities and company separately with symptoms.

Results

2,177 ecological momentary assessments revealed that leisure and social activities increased PA and decreased NA. We found increased affective instability between consecutive timepoints with increasing depression and anhedonia symptoms. Leisure and Social company predicted increases in PA and decreases in NA. Leisure activities and Social company led to greater reductions in NA with increasing depression symptoms, indicating a MB effect. Higher anhedonia predicted larger decreases in NA when engaged in leisure activities.

Conclusions

We provide real-world evidence that encouraging individuals with depression and anhedonia symptoms to engage in leisure activities and seek out enjoyable social company could elevate their mood via a reduction in NA.

Introduction

Leisure activities—those that are enjoyable, relaxing, and recreational—are linked to lower depression rates in the general population [1-5] and in patients [6, 7], compared to functional activities like work or chores. Frequently socialising with close friends or family appears to alleviate depression symptoms more effectively than being non-social (alone) or in larger groups [8-10]. Lab-based studies have shown that simulations of recreational and social activities can increase positive affect (PA) and decrease negative affect (NA) [11-14], suggesting that elevated mood underlies the positive effects of activity on depression symptoms.

Utilising Ecological Momentary Assessment (EMA), studies find that the real-life experiences of depression are characterised by higher levels and more variability in NA, greater inertia (moment-to-moment predictability) and lower levels of PA [15-17]. In addition, EMA studies have shown a "mood brightening" (MB) effect whereby events that are subjectively rated as being positive, lead to greater reductions in NA [18-24] and greater increases in PA [19, 25, 26] in depressed individuals compared to healthy controls. In contrast, other EMA studies have found no MB effect of positive events in depression [20, 23]. It is argued that this is due to participants subjectively rating events, as this could be confounded by negative biases in depression where patients tend to put greater weight on negative experiences compared to positive experiences [21]. Therefore, EMA studies that measure engagement in real-life activities could be more advantageous as they are more objective.

We know of only two studies examining NA and PA reactivity to actual activities using EMA. Heininga, Dejonckheere [27] examined PA reactivity to enjoyable activities grouped together (i.e. sport, hobbies, friends, partner), while van Loo, Booij [28] examined both NA and PA reactivity to physical (exercising, being outdoors) and social contexts (in company or alone) separately. Heininga et al. found no differences in PA reactivity to enjoyable activities in those with major depressive disorder (MDD) and anhedonia symptoms compared to controls. In contrast, van Loo et al. found a MB effect of physical activities which was driven by a greater decrease in NA, and a MB effect of social activities driven by a greater increase in PA and a greater decrease in NA, in depression compared to controls. This work suggests that physical and social activities might have MB effects through different mechanisms.

Inconsistencies in results to date might reflect differences in the measurement of NA and PA reactivity to activities. While van Loo, Booij [28] and Heininga, Dejonckheere [27] measured reactivity as in-the-moment affect, others have measured it as the difference between momentary affect and an individual's mean affect [18]. Further, some studies measured reactivity as the difference in affect between consecutive timepoints [20, 21]. This latter approach is akin to studies examining temporal instability using Mean Successive Squared Difference [MSSD; 29], which measures an individual's mean magnitude of the difference in affect between consecutive assessments. Previous studies have shown that poorer well-being is associated with NA and PA temporal instability [15], and that greater NA instability predicts higher depression symptoms [20, 30, 31] and greater suicidal ideation [32]. Together, this shows that temporal instability could be a biomarker of depression, and that stabilising affect may alleviate depression symptoms. However, as the MSSD collapses affective instability across all activities into a subject-level mean, we argue that the within-subject examination of how specific activities impact temporal instability is not known [33].

Therefore, the first aim of this study was to examine how depression symptoms moderate the within-subject relationship between activities (specifically leisure and social company) and temporal instability, by measuring reactivity as the change in NA and PA between consecutive assessments. This method allows us to measure both the *magnitude* and *direction* of change between consecutive assessments. So, a smaller magnitude of change, regardless of direction, would indicate lower instability. In contrast, increases and decreases in PA, for example, would both indicate high instability, but suggest elevated and lower mood, respectively. How NA and PA react to activities compared to a person's "general" experience is also unclear. Therefore, the second aim was to examine the within-subject relationship between activities (leisure and social company) and affective reactivity measured as the change in momentary NA and PA relative to the individual's mean affect. We examined if this was moderated by depression symptoms for leisure activities and social company separately.

To the best of our knowledge, no studies have examined the relationship between anhedonia symptoms and affective reactivity. Although Heininga and colleagues did include a group with both MDD and anhedonia, they reported mixed findings in PA reactivity when compared to controls [27, 34] and did not examine the dimensional relationship between affect and anhedonia symptoms.

Taken together and in line with previous studies, we hypothesised:

(H1) increased affective instability with increasing depression symptoms.

(H2) engaging in leisure activities and social company would lead to increases in PA and reductions in NA, relative to both baselines.

(H3) the increases in PA and reductions in NA when engaging in leisure activities and social company would be greater at higher depression symptoms, indicating an MB effect.

Methods

Sample.

2,426 questionnaires were collected from young people (N=95), ages 16-25, with a range of depression symptoms, recruited from the local schools and universities. As compliance thresholds are recommended to be between 30% and 60% [35-38], we set our threshold at 50% (at least 21 out of 42 assessments completed), also in agreement with other reactivity studies [27]. This gave us a final sample size of 71 participants and a total dataset of 2,177 EMA assessments.

The study adhered to ethical standards (Revised Helsinki declaration 2008) and was approved by the University of Reading Psychology Department Ethics Committee (REC no: 2021-120-CM). All participants provided written informed consent after reviewing the information sheets.

Patient & Public Involvement and Piloting.

Based on feedback from piloting sessions with young people, we revised the activity categories and allocated time for app troubleshooting in our study briefing sessions.

Baseline Demographics.

To assess depression symptoms, the Mood and Feelings Questionnaire [MFQ; 39] was used. The 33-item questionnaire has been shown to have excellent internal reliability in adolescents (Cronbach's α = 0.91 to 0.93) [40], where the scores range from 0 to 66 and higher scores indicating greater depression severity. It is a widely used and a validated questionnaire to examine depressive symptoms in young people.

To assess anhedonia symptoms, the Anhedonia Scale for Adolescents (ASA) was used, informed by qualitative interviews to specifically capture anhedonia in young people [41]. It contains 14 items rated on a four-point scale (0 = never, 1 = sometimes, 2 = often, 3 = always), and higher scores indicate more anhedonia symptoms. Scores range from 0 to 42. The total and subscales of ASA (1: Enjoyment, Excitement, and Emotional Flattening, 2: Enthusiasm, Connection, and Purpose, and 3: Effort, Motivation, and Drive) show good internal consistency (Cronbach's α = 0.79-0.94) and high test-retest reliabilities (ICC = 0.73-0.78) [41]. ASA subscale 2 was reverse-coded.

EMA Assessments.

We adapted the EMA protocol developed by Edwards, Cella [36] (Supplementary Methods for more details). In seven assessments per day for six days, participants reported their mood by rating "Right now, I feel [***…***]" statements using a Likert scale, ranging from 1 (not at all) to 7 (very much). We operationalised PA and NA by covering both high and low arousal states of emotions on the affective circumplex [42], consistent with previous studies [20, 27, 34, 43]. The selected items were: PA (high arousal: *cheerful, enthusiastic;* low arousal: *relaxed, satisfied*) and NA (high arousal: *annoyed, anxious;* low arousal: *ashamed, down*). The mean of these ratings per assessment represented the measure of momentary PA and NA. Participants also reported their current activities, selecting from multiple options for physical (Relaxing, Other Leisure Activities, Exercising, Work/School, Studying, Chores, Shopping, Hygiene, Eating/Drinking, Travelling) and social (Partner, Friends, Family, Alone) contexts. We categorised Relaxing, Other Leisure Activities and Exercising as "Leisure" and the rest as "Functional" physical activities, and we categorised Alone as "Non-Social", and the rest in the "Social" category.

Analysis.

We prepared EMA data for analysis using *esmpack* in R (https://wviechtb.github.io/esmpack/). From this, we presented the percentage of assessments engaged in each physical and social activity in pie charts, representing the split between Functional and Leisure activities, and Social and Non-social company.

To examine how affective reactivity is predicted by symptoms and activities, we measured reactivity as the *change* in momentary PA and NA, and ran separate multilevel linear models with it as the outcome. The change was measured relative to two baselines as used in prior studies: affect at the previous assessment (or, t-1) [44] and within-subject mean affect [45]. Both baselines provide the *direction* of change, affect (t-1) provides a measure of *temporal instability* of affect and mean affect represents how affect deviates from a subject's *general experience*.

In the multilevel linear models, Level 2 predictors were depression and anhedonia symptoms, and Level 1 predictors were the categories of physical activities (0 = Functional, 1 = Leisure) and company (0 = Non-Social, 1 = Social), and incorporated subject-level random intercepts. Each model included the *interaction* between activities/company and symptoms, and was controlled for baseline affect. Additionally, we controlled for depression symptoms in the models where ASA subscales were predictors, to isolate the relationship with anhedonia symptoms. These analyses were used to assess hypotheses H1-3.

Visual representation of how of the results are interpreted are described in Figure S2. Graphs show the interaction between symptom and activity/company with the shaded area representing the 95% confidence interval.

Lastly, to assess if the inertia of NA and PA drive their reactivity to Leisure activities and Social company, we ran the same multilevel models as above but also controlling for inertia. For details, see Supplementary Methods.

Results

Participants.

In a final sample size of 71 participants (mean age 20 yrs), we observed a mean compliance of 73% (Table 1).

Characteristics	Whole Sample (N = 71)
Age	20.14 (2.15)
Gender (% male)	28.2%
Gender split (F/M)	51/20
Compliance (%)	73 (12.3)
Assessment delay (mins.)	118 (41.03)
Ethnicity (n)	White = 56
	Black = 3
	Asian = 9
	Mixed = 2
	Other = 1
MFQ	26.22 (13.21)
ASA	18.46 (8.52)
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	7.51 (4.57)
Subscale 2 (Enthusiasm, Connection, and Purpose)	5.18 (1.96)
Subscale 3 (Effort, Motivation, and Drive)	5.77 (2.72)

Table 1: Mean (SD) unless stated otherwise. Whole Sample. Compliance threshold: >50%.

MFQ, Mood and Feelings Questionnaire; ASA, Anhedonia Scale for Adolescents.

Leisure activities and Social company in young people.

Leisure (relaxing, exercising and other leisure activities) and social (partner, friends and family) were ~50% of all activities that young people engaged in during the study period (Figure S1).

H1: Greater affective instability at higher depression symptoms.

Our hypothesis was confirmed as MFQ predicted greater increases in NA (Table 2; β = 0.032 and 0.036, p's<.001) and greater decreases in PA (Table S1), relative to the baseline of affect (t-1) across all activities and social company. Further, ASA total and subscales predicted decreasing PA (Table S1).

H2: Leisure activities and Social company predict a decrease in NA and an increase in PA.

This hypothesis was confirmed relative to the both baselines, affect (t-1) (Table S2a) and mean affect (Table S2b). All results indicate elevated mood.

H3: The MB effect of Leisure activities and Social company would be driven by both PA and NA reactivity.

Our findings partially confirm this hypothesis as they demonstrate that the MB effect was driven by NA reactivity. No interactions were observed for PA reactivity for either baseline affect (t-1) (Table S1) or mean affect (Table S3).

We found a negative interaction between leisure activities and MFQ (Table 2a; β = -0.01, p = .005) with the baseline NA(t-1). Together with the main effect of MFQ (β = 0.036, p<.001), this indicates a shallower slope when engaged in leisure activities, compared to functional activities (Figure 1). This suggests smaller increases in NA, and therefore lower temporal instability, at higher depression symptoms when engaged in leisure activities, compared to functional activities.

Further, we found a negative interaction between leisure activities and anhedonia symptoms, specifically we found (ASA Subscale 1, Table 2a; $\beta = -0.024$, $p = .01$), larger reductions in NA between consecutive assessments at higher anhedonia symptoms.

For the baseline of mean NA, negative interactions of MFQ with both Leisure activities (Table 3a; $\beta = -0.007$, $p = .014$) and Social company (Table 3b; $\beta = -0.005$, $p = .043$) were observed. This suggests that engaging in Leisure activities (Figure 2a) and Social company (Figure 2b) is associated with greater reductions in NA, below mean NA, at higher depression symptoms.

Inertia.

When controlling for inertia, all results for both baselines were similar to previous models without inertia (Tables S4-7). This indicates that reactivity to activities is not due to inertia of NA and PA.

Table 2a: Physical Activities	Symptom			Symptom x Leisure		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.036	0.005	<.001	-0.01	0.003	0.005
ASA Total	0.007	0.014	0.587	-0.011	0.005	0.025
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.022	0.027	0.433	-0.024	0.009	0.01
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.02	0.041	0.631	-0.035	0.022	0.114
Subscale 3 (Effort, Motivation, and Drive)	0.007	0.037	0.857	-0.026	0.016	0.105

Table 2b: Company	Symptom			Symptom x Social		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.032	0.005	<.001	-0.004	0.004	0.215
ASA Total	0.006	0.014	0.687	-0.005	0.005	0.299
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.021	0.028	0.462	-0.012	0.009	0.202
Subscale 2 (Enthusiasm, Connection, and Purpose)	0	0.041	0.995	0.002	0.023	0.914
Subscale 3 (Effort, Motivation, and Drive)	0.004	0.037	0.911	-0.019	0.016	0.229

Table 2: Outcome was the difference between momentary NA and baseline of NA(t-1), predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities or Company, and Symptoms predicted the outcome. In each model, baseline was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

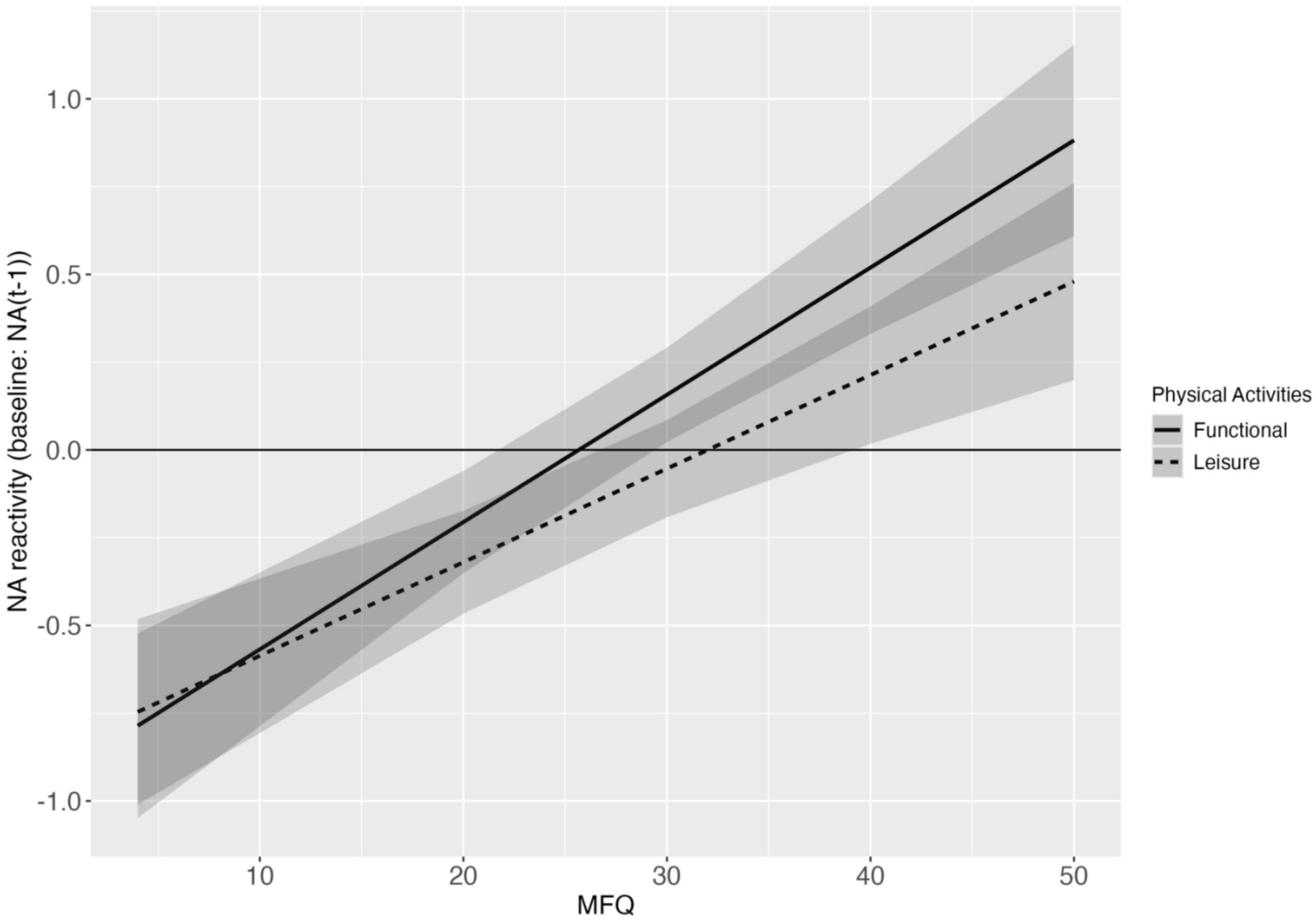

Figure 1: NA reactivity (baseline: NA(t-1)) showing the interaction of Depression Symptoms and Physical Activities. The slope of Leisure activities is shallower than Functional activities, showing smaller increases in NA between consecutive assessments when individuals with higher depression symptoms are engaged in Leisure activities. The shaded areas show standard error.

Table 3a: Physical Activities	Symptom			Symptom x Leisure		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.004	0.002	0.099	-0.007	0.003	0.014
ASA Total	0.004	0.004	0.404	-0.006	0.004	0.136
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.004	0.008	0.659	-0.013	0.008	0.086
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.017	0.014	0.244	-0.022	0.018	0.231
Subscale 3 (Effort, Motivation, and Drive)	0.009	0.012	0.421	-0.012	0.013	0.362

Table 3b: Company	Symptom			Symptom x Social		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.002	0.002	0.32	-0.005	0.003	0.043
ASA Total	0.002	0.004	0.582	-0.005	0.004	0.191
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.003	0.008	0.717	-0.01	0.008	0.171
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.008	0.014	0.558	-0.01	0.018	0.595
Subscale 3 (Effort, Motivation, and Drive)	0.008	0.012	0.513	-0.018	0.013	0.158

Table 3: Outcome was the difference between momentary NA and baseline of mean NA, predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, baseline was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

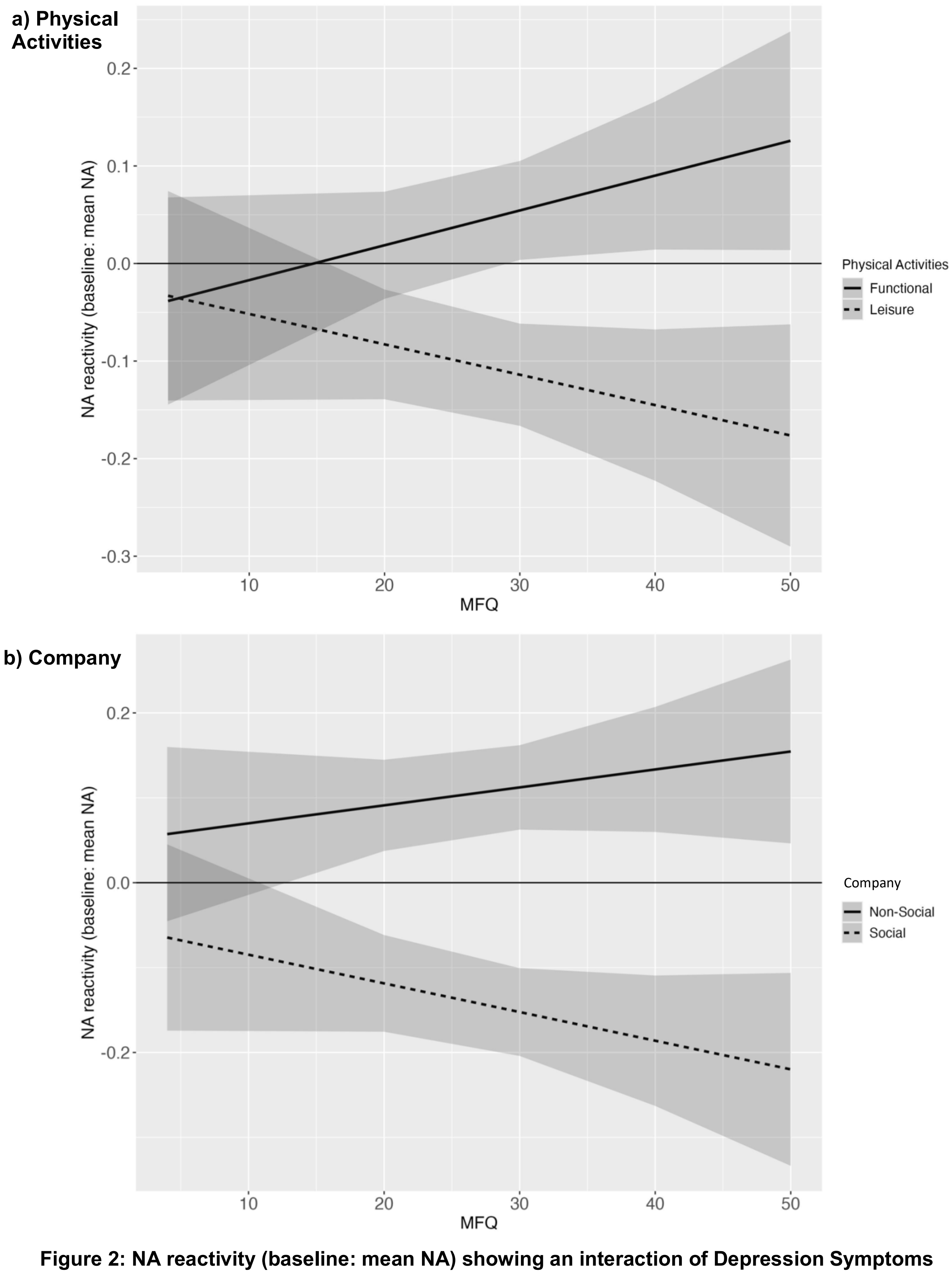

Figure 2: NA reactivity (baseline: mean NA) showing an interaction of Depression Symptoms and Activities. When engaged in a) Physical activities and b) Company, the significant interaction shows greater decreases below baseline in NA at higher depression symptoms.

Discussion

This study is the first to examine real life affective reactivity to leisure activities and social company in young people with depression and anhedonia symptoms.

In line with our hypothesis (H1), we found increased affective instability with increasing depression symptoms. This is consistent with studies showing greater NA instability associated with higher depression symptoms when measuring the mean *magnitude* of change between consecutive assessments using MSSD [20, 29-31]. We extend this by showing the temporal *direction* of change, i.e., greater increases in NA and greater decreases in PA between consecutive timepoints in those with higher depression symptoms. Further, we show for the first time that higher anhedonia symptoms predict greater decreases in PA between consecutive timepoints, in line with the role of positive processing as a mechanism that underpins anhedonia [46].

Regards hypothesis (H2), we found leisure activities and social company predict increases in PA and decreases in NA, compared to both the affect at the previous timepoint and mean affect. Thus, we show that doing enjoyable activities or being social can boost mood within a short timeframe (i.e. change from t-1), and above general mood experiences. This may underpin the well-established protective effects of leisure [1-5] and social company [9, 10, 47] against depression symptoms.

The hypothesis for H3 was partially confirmed, in that the MB effect of leisure and social company was driven by NA reactivity. The findings suggest that leisure activities reduce an increase in NA between consecutive assessments at higher depression symptoms, indicating lower temporal instability. As higher NA instability is shown to predict higher depression symptoms [20, 30, 31], this study is the first to demonstrate that leisure activities could reduce depression symptoms by stabilising NA. Further, we show that leisure and social company reduce NA, below mean NA, at higher depression symptoms.

Unlike van Loo, Booij [28], we did not find that PA reactivity underpins the MB effect of social company. However, van Loo et al. recruited a sample of over 400 adults and had double the number of people with depression and anxiety symptoms as we had in our study. This suggests that future studies with larger samples with depression symptoms are needed before firm conclusions can be drawn on the role of PA in the MB effect of social company in depression.

Depressed individuals show greater increases in NA to events appraised as being 'stressful' [43, 48, 49] and to negative interpersonal social events [50, 51]. As negative biases are considered a major player in maintaining depression [52, 53], our findings are consistent, showing that NA is the more reactive affective component of mood in depression. Further, our results are promising, as they show that the moderation of NA by leisure and social company could be a mechanism by which these activities improve mood.

An interesting finding was that higher anhedonia (Subscale 1 of ASA, Enjoyment, Excitement, and Emotional Flattening) predicted larger decreases in NA between consecutive assessments when engaged in leisure activities. This supports the notion that engaging in leisure activities can help anhedonia via reductions in NA and is in line with young people's views on the effects of brief BA treatment for anhedonia [54]. Acting, despite having low motivation, was generally helpful as the young people described enjoying activities when they were involved in them. They said this gave them a direct experience of positive reinforcement, allowing them to shift their association of hobbies with negative emotions to positive emotions [54].

As most of our sample was female, our findings cannot be generalized across all young people. Moreover, we recognise that an event-specific measure of affect would help distinguish between the effects of social and activity contexts on affect, as shown by Dejonckheere, Mestdagh [55], i.e. "when engaged in your current activity, how [*enthusiastic*] do you feel?".

Taken together, our results support encouraging individuals with depression symptoms to engage in leisure activities and seek out enjoyable social company to reduce their symptoms via a reduction in NA. Further, our work suggests that engaging in leisure activities and social company could protect against overwhelming negative affect in young people helping them become more resilient to future episodes of depression.

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Conflicts of interests:

The authors report no conflicts of interest.

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3.2. Supplementary Methods & Results

Negative Affect Drives The Mood Brightening Effect Of Leisure And Social Activities In Young People With Depression And Anhedonia Symptoms: An Ecological Momentary Assessment Study

Sahni A, McCabe C.

Supplementary Methods

EMA Procedure.

The experimenter met with each participant to brief them on the app. Participants were then required to log on and fill in their age, gender, ethnicity and the Mood and Feelings Questionnaire [MFQ; 1] and Anhedonia Scale for Adolescents [ASA; 2] questionnaires. EMA assessments began the next day. Participants were asked to respond to each assessment as soon as possible, otherwise they would expire.

We collected data 7 times a day, between 8:30am and 10pm, for 6 days, during the period July 2022 to Oct 2023. There was at least 45 min delay between each semi-random assessment which took approx. 1 min to complete and expired after 20 minutes. This sampling frequency and questionnaire design has been shown to encourage compliance and reduce burden in young people and those with mood disorders [3-6]. We contacted participants on days 2 and 5 to check that they were receiving notifications and to troubleshoot any problems.

At the end of the study, we collected app user experiences and participants were debriefed and advised that if concerned about their mood to contact their GP or the mental health charity the Samaritans.

Physical Activities and Social Contexts.

To examine how much time is spent in each category of activity, and therefore in Leisure activities and Social company, we presented the data of the percentage of assessments in each activity across the whole sample.

Multilevel Models.

The structure of the multilevel models was similar across the study. In every model, only subject-level random intercepts were considered as the random effects. The outcomes varied, depending on what was being examined. To examine reactivity/instability in H1 to H3, the outcome was the *difference* from the baseline. These are specified in each model, i.e. affect (t-1) or mean affect.

The fixed effects (or predictors) were at Level 2, if considering symptoms. For depression symptoms, MFQ was the predictor but, in order to isolate anhedonia symptoms from depression symptoms, we would control the MFQ for the Anhedonia Scale for ASA and its subscales. In each model, we always controlled for the baseline. Regarding activities, and as stated in the Methods section of the paper, we classified physical activities and company into 2 separate categories. For physical activities, Leisure (coded as 1; relaxing, other leisure and exercise) and Functional (coded as 0; work/school, studying, chores, shopping, hygiene, eating/drinking, travelling); for social company, Social (coded as 1; partner, friends, family) and Non-social (coded as 0; alone). The interactions of activities/company with symptoms were used to determine if a mood brightening (MB) effect was present.

Affective Inertia.

Finally, we conducted the further analyses to control for the effects of affective inertia on reactivity of NA and PA. For this, we determined the within-subject correlations between consecutive timepoints of NA and PA, by applying the Spearman's method. The correlation coefficient per subject then gave us a Level 2 variable to control for in the multilevel models described above.

We did not consider other dynamics of affect as they would be non-dissociable from our measures of reactivity. These include instability, measured by mean square successive difference [MSSD; 7], which is covered by the Affect (t-1) baseline as it contains the same temporal component that MSSD captures. Another is variability (or standard deviation (SD) of affect), which is akin to our reactivity measures which capture the *difference* in current affect from a baseline. Variability is simply the *non-*

temporal version of our reactivity measures, so we did not deem it a necessary factor to control for.

Inertia, however, seems to be an interesting dynamic, capturing the *trend* of affective change between assessments. To examine if inertia of affect at previous timepoint was responsible for the reactivity at current timepoint, instead of the activity being engaged in, we chose to control for inertia.

Supplementary Results

Figure S1. Physical Activities and Company.

Leisure activities and Social company (*white*), and Functional activities and Non-Social company (*grey*) across the whole sample. Young people spent half of their test period engaged in activities in each category. This was calculated as the number of assessments spent in each activity.

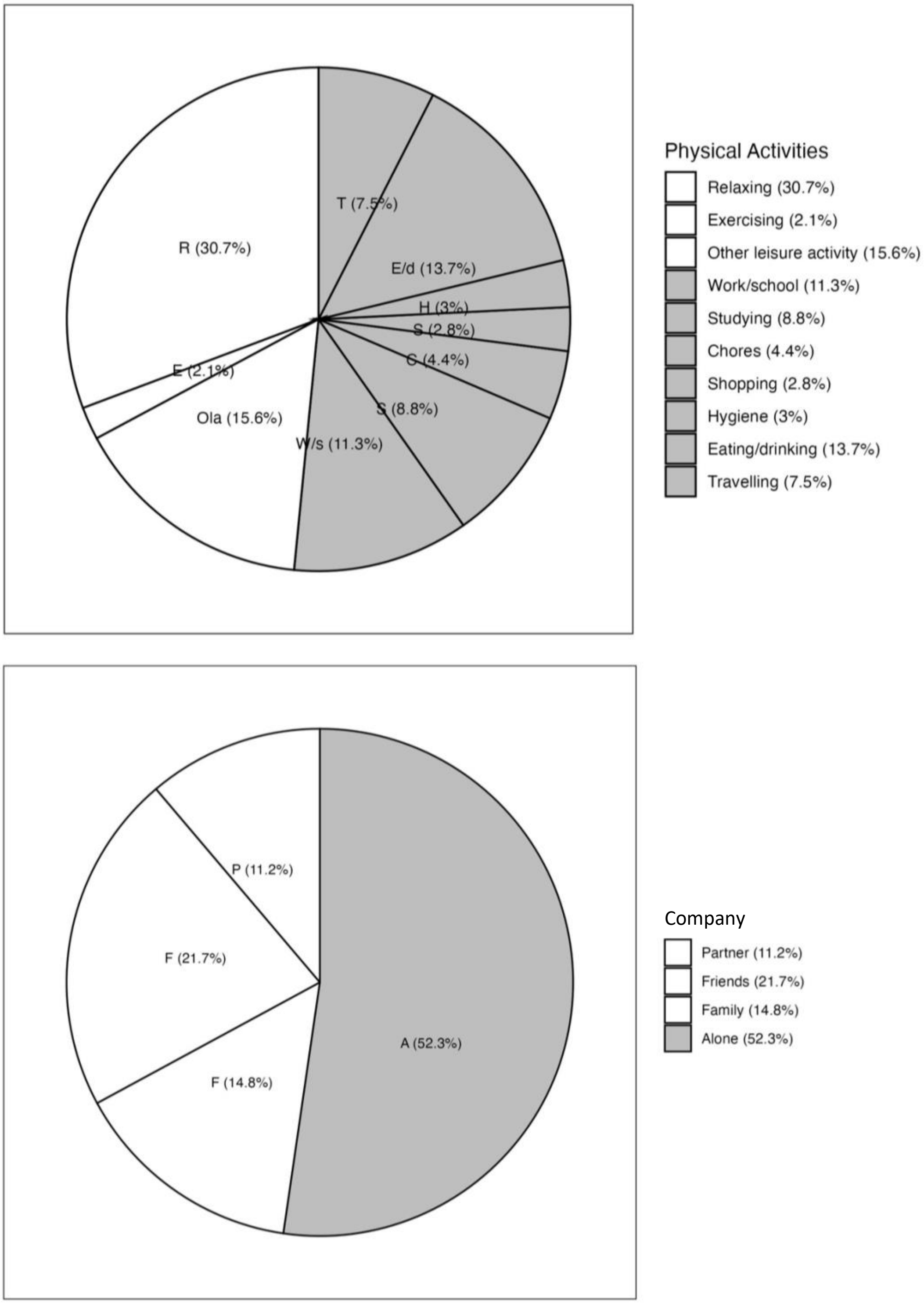

Figure S1: Leisure activities and Company that young people spent their time engaged in.

Figure S2. Interpretation of Results from Multilevel Models of Affective Reactivity.

The interactions between symptoms and contexts (physical activities, social company) are the results that assess the mood brightening (MB) effect, which are graphically shown in this paper like Figure S2. For full and dashed black lines, the positive slopes suggest that the increase in affect is greater at higher depression symptoms, whereas the dashed blue line's negative slope shows that the decrease in affect is greater at higher depression symptoms (Figure S2). The MB effect is specifically if the *increases in PA* or *decreases in NA* are greater at higher depression symptoms, as both result in elevated mood in depressed individuals. Further, the interpretations of results depend on the baseline used to measure the reactivity.

For affect (t-1) as baseline, comparing the full black line and the dashed black line shows that engaging in context B *dampens the increase in affect* compared to context A, across the whole sample (Figure S2). This implies that engaging in context B *reduces the temporal instability* compared to context A. However, comparing full black line and blue dashed line shows that engaging in context B results in *decreases in affect* between consecutive assessments, whereas engaging in context A is associated with *increases in affect* (Figure S2). This implies that contexts differ in the *direction* of affective change, but implies nothing about temporal instability.

Similarly, for mean affect as baseline, comparing full black line and blue dashed line implies that context B predicts a *decrease in affect below an individual's general experience*, whereas context A predicts an *increase* in affect (Figure S2). Lastly, comparing full and dashed black lines, we interpret that the *increases in affect above an individual's general experience* is greater in context A than context B.

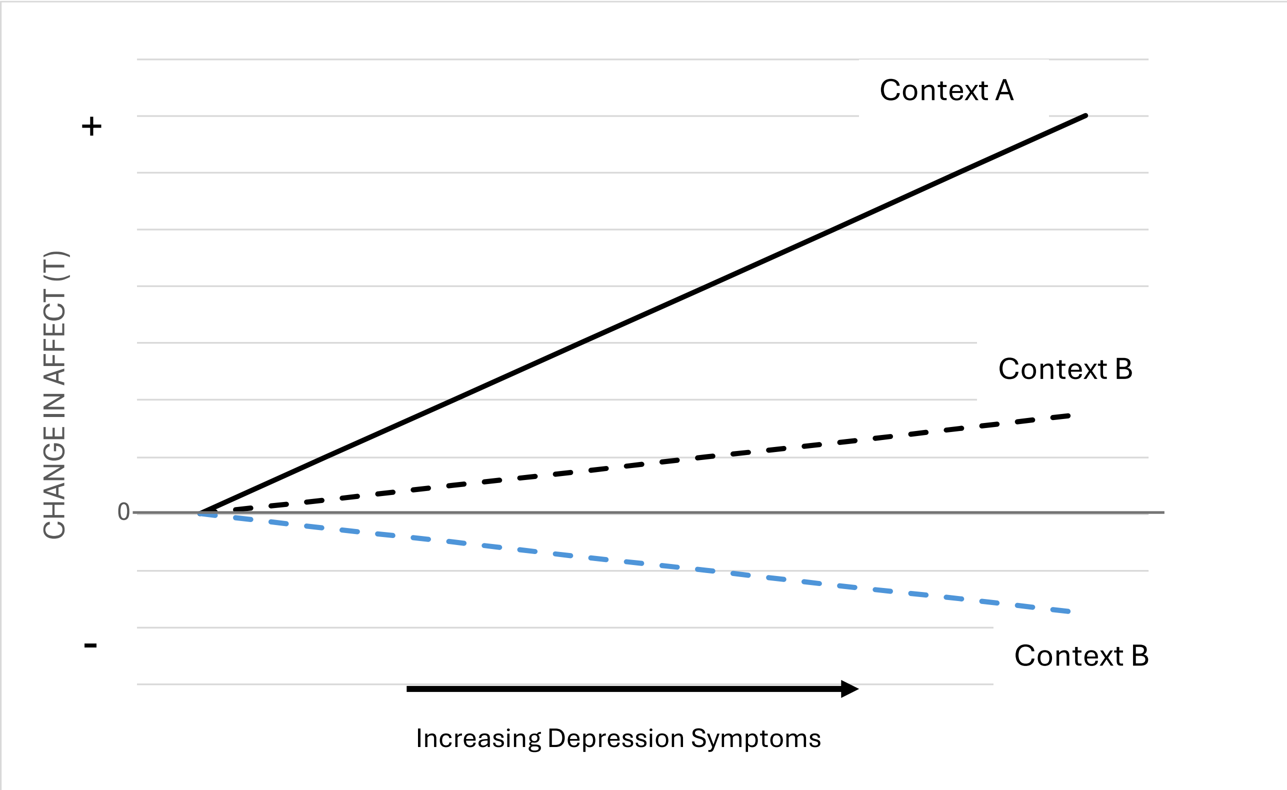

Figure S2: Visual representation of the interaction between depression symptoms and context. Contexts A and B represent the binary options for physical activities (Leisure, Functional) and social company (Social, Non-Social). The dashed lines show that the changes in affect are *smaller* than full lines, as the slopes are shallower.
Note, that all line show that the changes in affect are greater at higher depression symptoms, suggesting a mood brightening (MB) effect.

Table S1. (H1 & H3) Instability of PA Predicted by Symptoms and Contexts.

Using affect (t-1) as baseline, we ran multilevel linear models with an interaction between activities and symptoms predicting reactivity. The activities were coded as follows: Physical (0 = Functional, 1 = Leisure) and Social (0 = Non-Social, 1 = Social). As hypothesised for H1, higher depression symptoms predicted greater instability in PA (Table S1a & b; β = -0.015 and -0.016, p's < .01). Further, the direction of the effects (or β) indicate that PA decreases, relative to affect at the previous timepoint, at higher depression symptoms (interpreted using Figure 2). Similar to Table S1, we found that anhedonia symptoms (ASA subscales) specifically predicted greater PA instability.

For H3, we expected to find an MB effect of Leisure activities and Social company, i.e. an interaction of activities and symptoms that show increased PA and decreased NA. However, the only significant interaction we observed was of depression symptoms with Leisure activities for NA reactivity (See Main paper, Table 2a; β = -0.01, p = .005). No significant interactions were seen for PA reactivity (Table S1).

Table S1a: Physical Activities	Symptom			Symptom x Leisure		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	-0.015	0.005	0.008	0	0.004	0.959
ASA	-0.04	0.014	0.005	0.004	0.006	0.477
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	-0.068	0.028	0.017	0.003	0.011	0.798
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.123	0.041	0.004	0.04	0.027	0.134
Subscale 3 (Effort, Motivation, and Drive)	-0.075	0.038	0.052	0.014	0.019	0.465

Table S1b: Company	Symptom			Symptom x Social		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	-0.016	0.005	0.003	0.002	0.004	0.587
ASA	-0.038	0.013	0.005	0.008	0.006	0.168
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	-0.072	0.027	0.009	0.017	0.011	0.117
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.1	0.041	0.017	0.021	0.027	0.44
Subscale 3 (Effort, Motivation, and Drive)	-0.07	0.037	0.062	0.023	0.019	0.235

Table S1: Outcome was the difference between momentary PA and baseline of PA(t-1), predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, baseline was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

Table S2. (H2) NA and PA Reactivity Predicted by Leisure Activities and Social Company.

Reactivity is denoted as the change in affect (NA and PA) and, in all models, baselines were controlled for. As hypothesised for H2, we found that engaging in Leisure activities and Social company, predicted increased PA and lowered NA relative to affect (t-1) (Table S2a) and mean affect (Table S2b) as baselines.

	PA			NA		
	β	**SE**	**p**	**β**	**SE**	**p**
Leisure	0.245	0.053	<.001	-0.179	0.044	<.001
Social	0.405	0.054	<.001	-0.249	0.045	<.001

Table S2a: The outcome was the change in momentary affect vs. baseline of affect(t-1). Predicted by Leisure (compared to Functional), Social (compared to Non-Social).

	PA			NA		
	β	**SE**	**p**	**β**	**SE**	**p**
Leisure	0.19	0.041	<.001	-0.143	0.035	<.001
Social	0.4	0.041	<.001	-0.245	0.035	<.001

Table S2b: The outcome was the change in momentary affect vs. baseline of mean affect. Predicted by Leisure (compared to Functional), or Social (vs. Non-Social).

Table S3. (H3) PA Reactivity Against Mean PA Predicted by Symptoms and Contexts.

Using mean PA as baseline, we ran multilevel linear models with an interaction between activities and symptoms predicting reactivity. No significant results were seen, indicating no significant effect of symptoms nor an interaction effect (Table S3). Together with the results of Table S1, this finding suggest that PA reactivity does not contribute to the MB effect. However, interactions effects on NA reactivity (vs. both baselines) shows that our hypothesis (H3) was partially accurate.

Table S3a: Physical Activities		**Symptom**			**Symptom x Leisure**	
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0	0.002	0.974	0.001	0.003	0.75
ASA	0.001	0.005	0.825	0.001	0.005	0.855
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.008	0.01	0.446	0	0.009	0.987
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.011	0.017	0.527	0.017	0.021	0.41
Subscale 3 (Effort, Motivation, and Drive)	-0.001	0.014	0.961	0	0.015	0.996

Table S3b: Company		**Symptom**			**Symptom x Social**	
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	-0.002	0.002	0.428	0.004	0.003	0.214
ASA	-0.001	0.005	0.838	0.008	0.005	0.092
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0	0.01	0.973	0.016	0.009	0.072
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.016	0.016	0.342	0.035	0.021	0.09
Subscale 3 (Effort, Motivation, and Drive)	-0.002	0.014	0.866	0.015	0.015	0.3

Table S3: Outcome was the difference between momentary PA and baseline of mean PA, predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, baseline was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

Table S4 & S5. Controlling for Inertia, NA (S4) and PA (S5) Instability Predicted by Symptoms and Contexts.

For the baseline of affect (t-1), the pattern of results is the same when controlled for inertia as they were without it, for the *interactions*: the negative interactions of depression and anhedonia (ASA Subscale 1) symptoms with Leisure for NA instability indicate decrease in NA between consecutive assessments (Table S4a); this is similar to the finding of blunted increase in Leisure activities as shown in Table 2a. This suggests that NA reactivity, and not inertia from previous timepoint, drives the MB effect of Leisure activities.

Unlike results in Table S1, when controlled for inertia, greater instability (tending to decrease) of PA was not predicted by depression or anhedonia symptoms (Table S5). This is expected, as instability and inertia are similar dynamics owing to the temporal component (t and t-1) in both measures. Controlling for temporal dynamics will diminish any PA instability that we had expected to find. As before, no interaction effects were found with Leisure or Social for PA instability, again suggesting the absence of PA reactivity in the MB effect.

Table S4a: Physical Activities	Symptom			Symptom x Leisure		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.005	0.003	0.078	-0.009	0.004	0.02
ASA	0.012	0.006	0.061	-0.015	0.006	0.012
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.021	0.012	0.087	-0.034	0.011	0.002
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.036	0.021	0.089	-0.038	0.027	0.163
Subscale 3 (Effort, Motivation, and Drive)	0.026	0.018	0.145	-0.034	0.019	0.077

Table S4b: Company	Symptom			Symptom x Social		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.001	0.003	0.724	-0.004	0.004	0.344
ASA	0.009	0.006	0.139	-0.007	0.006	0.255
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.021	0.012	0.089	-0.018	0.011	0.104
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.006	0.021	0.788	0.011	0.027	0.677
Subscale 3 (Effort, Motivation, and Drive)	0.023	0.018	0.207	-0.021	0.019	0.267

Table S4: Outcome was the difference between momentary NA and baseline of NA(t-1), predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, inertia was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

Table S5a: Physical Activities	Symptom			Symptom x Leisure		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0	0.003	0.885	0.003	0.005	0.601
ASA	-0.004	0.007	0.544	0.011	0.007	0.128
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	-0.007	0.014	0.62	0.017	0.013	0.202
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.037	0.025	0.131	0.063	0.032	0.052
Subscale 3 (Effort, Motivation, and Drive)	-0.004	0.02	0.856	0.029	0.023	0.207

Table S5b: Company	Symptom			Symptom x Social		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.001	0.003	0.751	0.001	0.005	0.868
ASA	-0.001	0.007	0.849	0.004	0.007	0.568
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	-0.01	0.014	0.478	0.013	0.013	0.319
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.009	0.025	0.73	-0.021	0.032	0.504
Subscale 3 (Effort, Motivation, and Drive)	0.006	0.021	0.755	0.013	0.022	0.559

Table S5: Outcome was the difference between momentary PA and baseline of PA(t-1), predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, inertia was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

Table S6 & S7. Controlling for Inertia, NA (S6) and PA (S7) Reactivity Against Mean Affect Predicted by Symptoms and Contexts.

Just as in Table S4, no main effects of symptoms or interactions with activities were observed in PA reactivity when controlled for inertia with mean PA as baseline (Table S7). Again, similar to previous results, negative interactions of Leisure (Table S6a) and Social (Table S6b) activities with depression symptoms was observed for NA reactivity, suggesting greater reductions in NA below mean NA for those with higher depression symptoms. With models controlled for inertia, this again confirms that NA reactivity drives the MB effect of Leisure and Social activities, which is not driven by the affective inertia from the previous timepoint.

Table S6a: Physical Activities	**Symptom**			**Symptom x Leisure**		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.003	0.002	0.15	-0.007	0.003	0.015
ASA	0.004	0.004	0.412	-0.006	0.004	0.147
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.003	0.009	0.692	-0.013	0.008	0.094
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.017	0.014	0.238	-0.022	0.018	0.237
Subscale 3 (Effort, Motivation, and Drive)	0.01	0.012	0.42	-0.011	0.013	0.389

Table S6b: Company	**Symptom**			**Symptom x Social**		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.002	0.002	0.375	-0.006	0.003	0.036
ASA	0.003	0.004	0.495	-0.006	0.004	0.17
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.004	0.008	0.647	-0.011	0.008	0.152
Subscale 2 (Enthusiasm, Connection, and Purpose)	0.009	0.014	0.503	-0.011	0.018	0.55
Subscale 3 (Effort, Motivation, and Drive)	0.01	0.012	0.423	-0.019	0.013	0.145

Table S6: Outcome was the difference between momentary NA and baseline of mean NA, predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, inertia was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

Table S7a: Physical Activities	**Symptom**			**Symptom x Leisure**		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	0.001	0.002	0.788	0	0.003	0.902
ASA	0	0.005	0.982	0	0.005	0.948
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.005	0.01	0.597	-0.001	0.009	0.912
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.012	0.017	0.466	0.015	0.021	0.487
Subscale 3 (Effort, Motivation, and Drive)	-0.002	0.014	0.91	-0.002	0.015	0.907

Table S7b: Company	**Symptom**			**Symptom x Social**		
Symptoms	**β**	**SE**	**p**	**β**	**SE**	**p**
MFQ	-0.001	0.002	0.662	0.004	0.003	0.22
ASA	0	0.005	0.929	0.008	0.005	0.095
Subscale 1 (Enjoyment, Excitement, and Emotional Flattening)	0.001	0.009	0.931	0.016	0.009	0.073
Subscale 2 (Enthusiasm, Connection, and Purpose)	-0.014	0.016	0.395	0.035	0.021	0.091
Subscale 3 (Effort, Motivation, and Drive)	-0.001	0.013	0.956	0.015	0.015	0.317

Table S7: Outcome was the difference between momentary PA and baseline of mean PA, predicted by symptoms, and a) Physical activities (0 = Functional, 1 = Leisure), and b) Company (0 = Non-Social, 1 = Social).
Each symptom signifies a separate multilevel linear model, in which an interaction between Activities and Symptoms predicted the outcome. In each model, inertia was controlled. For ASA scale, depression symptoms (MFQ) were additionally controlled for.

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4. Paper 3

Anhedonia is Associated with Computational Impairments in Reward and Effort Learning in Young People with Depression Symptoms

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Background: Anhedonia and depressive symptoms have been linked to potential deficits in reward learning. However, how anhedonia impacts the ability to adjust and learn about the effort required to obtain rewards remains poorly understood.

Methods: We examined young people (N = 155, 16 to 25 yrs.) with a range of depression symptoms, using a probabilistic instrumental learning task. The task consisted of two counterbalanced blocks during which participants were asked to learn which option to choose to maximize reward receipt or to minimise the physical effort required to obtain the rewards, respectively. We compared the exerted effort (button pressing speed) for high (puppy images) vs low (dog images) rewards and collected subjective reports of "liking", "wanting" and "willingness to exert effort" for these rewards. Computational models were fit to the learning data and model parameters, as well as task measures, were correlated with depression and anhedonia symptoms.

Results: We found that, as depression symptoms and consummatory anhedonia increased, liking of high rewards (puppy images) decreased and as anticipatory anhedonia increased, liking, wanting and willingness to exert effort for puppy images decreased.

Participants exerted more effort for high rewards than for low rewards, as expected, but at higher anticipatory anhedonia levels this difference was diminished.

Regarding the task performance, we observed that, as depression symptoms increased, reward learning accuracy decreased. Moreover, higher consummatory anhedonia was associated with worse reward and effort learning, as well as with increased temperature parameter values for both reward and effort learning.

Conclusion: We provide novel evidence that anhedonia is associated with difficulties in modulating effort exertion as a function of reward value. As indicated by increased temperature parameters, our findings are also the first to show the computational mechanisms underpinning anhedonia and its association with the under-exploitation of low effort options and of high rewards. We suggest that addressing the biases in the exploration/exploitation behaviour in depressed and anhedonic young people could be targets for novel interventions.

Key words: Anhedonia, depression, youth, learning, reward, effort, adolescent.

Introduction

Depression is the leading cause of illness and disability worldwide (World Health Organization, 2017). Anhedonia, a lack of interest and pleasure, is a core symptom of depression (American Psychiatric Association, 2013) and is characterised by blunted liking and wanting of rewards in adults (Argyropoulos & Nutt, 2013; Kaya & McCabe, 2019; Rizvi et al., 2016; Treadway & Zald, 2011) and young people (Ely et al., 2021; Forbes & Dahl, 2012; Kaya & McCabe, 2019; Ma et al., 2024; McCabe, 2018). Deficits in reward learning have also been observed in depression (Kumar et al., 2018; Thomsen, 2015) and have been linked to anhedonia (Kangas et al., 2022). However, it remains unclear how learning about the effort required to attain rewards may be associated with depression or anhedonia symptoms.

Depressed individuals fail to exert more effort for higher or more likely rewards (Horne et al., 2021), which suggests poor effort modulation as a function of reward. Anhedonia has been shown to be associated with lower physical effort exertion and willingness to expend effort (making low effort/low reward choices) for monetary rewards in both adults (Cléry-Melin et al., 2011; Darrow et al., 2023; Geaney et al., 2015; Tran et al., 2021; Treadway et al., 2012; Yang et al., 2014) and young people (Bryant et al., 2017; Olino et al., 2021; Slaney et al., 2023; Treadway et al., 2009). We have extended these findings by showing that anhedonia in young people is also associated with less physical effort exertion (button presses) for primary rewards, such as chocolate (Rzepa & McCabe, 2019), and less subjective willingness to exert effort (rated on a visual analogue scale) for puppy images (Frey et al., 2023a).

Although few studies have examined reward and effort learning in depression, a recent study using learning tasks with reward and punishment outcomes, and effort and delay costs, found reduced physical and cognitive effort exertion for monetary reward in depression (Vinckier et al., 2022). Further, utilising computational modelling, Vinckier et al. found that, compared to controls, depressed individuals demonstrated a higher sensitivity to effort cost, which was measured as the mean aversive value of effort items in preference tasks and as the weight of effort cost on net expected value in performance tasks. However, when examining participants' ability to update choices to maximize monetary gain (reward learning) and minimize monetary loss (punishment learning), no significant correlation was found with anhedonia symptoms, which the authors suggest could be due to the small sample size.

To extend this past work, the aim of this study was to combine, for the first time, our recently adapted reward and effort learning task (Frey et al., 2023a) with a computational modelling approach. Our task is based on a probabilistic learning task from Skvortsova et al. (2017; 2014), which we previously adapted from utilising monetary outcomes to including primary rewards (chocolate and puppy images). With this task, we found that higher anticipatory anhedonia was significantly associated with lower reward learning accuracy (Frey et al., 2023a). However, we did not observe a significant association between depression or anhedonia symptoms and effort learning, which may have been the case because the task was too challenging with an interleaved design. Specifically, participants needed to switch between learning about reward and effort from trial to trial, which may have led to a trade-off between effort and reward learning. As the primary rewards used in the task were particularly salient, participants' attention may have been shifted towards learning from rewards, rather than from effort outcomes. To address this issue, the current study aimed to further adapt the task into a block design that separates reward and effort learning.

Using computational modelling, we aimed to examine the relation between depression and anhedonia and various parameter values that capture different aspects of learning. Several previous studies have reported that depression and anhedonia symptoms are associated with lower reward sensitivity parameters (Chen et al., 2015; Q. J. M. Huys et al., 2013; Katz et al., 2020). However, findings regarding reward learning rates, the weight given to unexpected outcomes that modulate future actions, have been inconsistent. Some studies find higher (Beevers et al., 2013) and others lower (Chen et al., 2015; Cooper et al., 2014; Frey et al., 2021) learning rates in depression, compared to controls. In line with these inconsistencies, recent meta-analysis examining reinforcement learning parameters from decision making tasks with reward and punishment outcomes found no differences in learning rates between patients with depression or anxiety and controls (Pike & Robinson, 2022). However, this may partly have been the case because the studies included in the meta-analysis differed in terms of the tasks and computational models used. To account for this, the authors employed a novel meta-analytic method to estimate the learning rates. Using this simulated approach, higher punishment learning rates and slightly lower reward learning rates were found in patients compared to control individuals (Pike & Robinson, 2022).

Another parameter often examined is temperature (i.e., when temperature parameter τ becomes large, the selections become more random and exploratory), which governs the extent to which individuals select high-valued actions or explore lower-valued alternatives. Some studies find that depressed individuals make more random choices (Kunisato et al., 2012; Rupprechter et al., 2018). Using a conventional meta-analysis design, Pike and Robinson 2022 found lower inverse temperature (i.e., lower inverse temperature implies that selections become more random) in patients, compared to controls; yet, this effect was not apparent in the simulated meta-analysis (Pike & Robinson, 2022).

Although there are many studies examining learning in depression with a computational modelling approach, few have specifically assessed the relation between anhedonia and computational model parameters. Moreover, we are aware of no studies examining the relationships between effort learning parameters and depression or anhedonia symptoms. Therefore, the current study aimed to specifically investigate the relation between depression and anhedonia symptoms and effort, as well as reward, learning accuracy and parameter values. Based on previous studies, we hypothesised lower reward learning rates and higher temperature with increasing depression and anhedonia symptoms. As effort is considered a cost (Pessiglione et al., 2017), we also hypothesised higher effort learning rates with increasing depression symptoms. In addition, in line with our and others' findings, we hypothesised that young people with higher levels of depression and anhedonia would show lower subjective liking, wanting and willingness to exert effort for rewards.

Methods

Participants

Using G*Power we calculated a sample size of at least 84 participants was required to examine correlations between task measures and symptoms, with a medium effect size of 0.3, 80% power and $\alpha = 0.05$.

Young people (N = 155) between the ages of 16 and 25 years, with a range of depression symptoms, were recruited from local schools and the university student population via the School of Psychology research panel, online advertisements, and posters displayed throughout the university.

We complied with the School of Psychology Research Ethics committee ethical standards (ref no: 2023-150-CM) and with the Helsinki Declaration of 1975, as revised in 2008. After reading the information sheets, all participants provided informed consent.

University participants were reimbursed for their time with course credits or were entered into a draw for a £20 Amazon voucher. All participants received a debrief sheet, which advised those concerned about their mood to contact their GP and provided contact details for the Samaritans.

Questionnaires

Participants filled out a demographics form, and the following questionnaires online: the Beck Depression Inventory-II (BDI; Beck et al., 1961), the Temporal Experience of Pleasure Scale (Gard et al., 2006) , and the Snaith–Hamilton Pleasure Scale (Snaith et al., 1995).

High scores on the BDI indicate more severe depression symptoms, with validated and well-established psychometric properties. High scores on the TEPS indicate lower anhedonia symptoms, while high scores on the SHAPS indicate higher anhedonia symptoms. Good internal consistency, test–retest reliability, and convergent and discriminant validity have been shown for both the TEPS anticipatory and consummatory subscales (Gard et al., 2006), and the SHAPS (Nakonezny et al., 2010).

After completing the questionnaire measures, participants were sent a link to the online learning task described below and were asked to complete the task on a PC or a laptop.

Learning task

We adapted a probabilistic instrumental learning task from Skvortsova et al. (2014), substituting monetary reward for images of puppies and dogs as high and low rewards, respectively. We found in our previous study that young people regard puppy images as rewarding, and as more rewarding than images of dogs (Frey et al., 2023b), in line with past reports that baby animals are consistently rated as more pleasant than adult animals (Lehmann et al., 2013).

We simplified the task by separating the reward and effort learning trials into two separate blocks, as we (Frey et al., 2023b) and others (Skvortsova et al., 2014) have observed that participants find it difficult to simultaneously learn about reward and effort in an interleaved design.

Before the task, subjects were asked to rate the reward stimuli on a visual analogue scale ranging from 0 to 100. Specifically, they were asked to indicate how much they *liked* looking at the puppy images, how much they *wanted* to see the puppy images, and how much *effort they were willing to exert* to look at the puppy images. These ratings were collected again at the end of the experiment.

Each trial started with a choice of two shapes, pressing 'C' selected the left shape and pressing 'M' the right shape. In the reward learning block, one shape was associated with high reward (puppy image) 75% of the time and low reward (dog image) 25% of the time, while the other shape was associated with high reward (puppy image) 25% of the time and low reward (dog image) 75% of the time. The effort level was fixed (100% high/60 button presses) for both shapes. In the effort learning block, one shape was associated with high effort (60 button presses) 75% of the time and low effort (35 button presses) 25% of the time, while the other shape was associated with high effort (60 button presses) 25% of the time and low effort (35 button presses) 75% of the time. The reward was fixed (100% high/puppy images) for both shapes. The order of the blocks and the shape pairs were randomised per participant and which shape (left or right) was associated with the higher contingency was counterbalanced between the blocks. Participants were instructed to choose the shapes that resulted in receiving high rewards in the reward block and in the lowest effort requirement in the effort block.

Once a choice was made, participants were informed about the outcome, i.e., the reward and effort levels were shown on the screen (high reward: puppy line drawing, low reward: dog line drawing, low effort: a small rectangular bar to fill up, high effort: a larger rectangular bar to fill up; see Figure 1). Next, participants needed to exert effort to obtain the reward by alternatively pressing the ‘C’ and ‘M’ keyboard buttons, which led to a blue bar filling up the rectangle. On high effort trials, filling up the rectangle required 60 button presses, while on low effort trials only 35 button presses were needed. After participants reached the effort target, they received the actual reward (seeing a photograph of a puppy or dog).

Overall, the task consisted of 4 practice trials followed by 50 experimental trials (block 1 with 25 trials, 30 s break, block 2 with 25 trials) and took ~30 minutes to complete. Based on previous research using similar tasks, 25 trials seemed sufficient to allow participants to learn the contingencies in the simplified block design without making the tasks so long as to cause fatigue.

The data generated consisted of the task measures of reward and effort learning accuracy, and speed of effort key presses for high and low rewards.

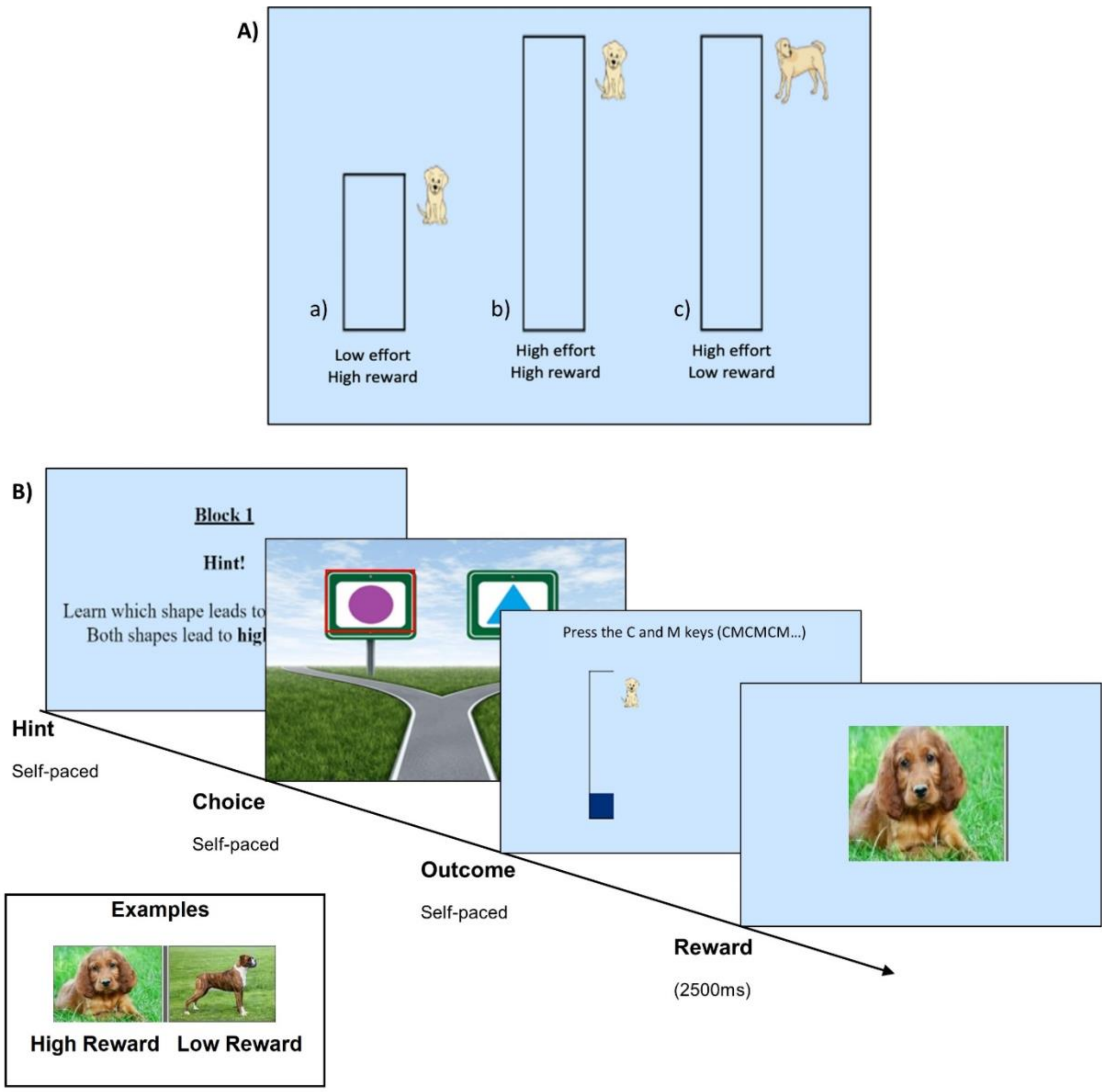

Figure 1: Task Structure**. A)** possible outcomes associated with choices, and **B)** procedure of each trial. The 30-second break separated the reward and effort learning blocks. For 'self-paced' phases, the participant's action (i.e. making a choice or filling up the effort rectangle) determined when the task moved on to the next stage.

Analysis

All data were examined using R (version 4.3.2). To check for habituation effects, we used a repeated-measures ANOVA with rating type (liking, wanting, willingness to exert effort) and time (pre or post task) as within-subject factors and the difference in ratings (i.e. ratings for high rewards minus low rewards) as the dependent variable.

We conducted correlations between symptoms, subjective ratings and task measures. When examining anhedonia, we controlled for depression (with the following 4 anhedonia items removed from the BDI: loss of pleasure, loss of interest, loss of energy, and interest in sex, as in (Winer et al., 2014)).

We also examined if accuracies differed between the effort and reward learning blocks, while controlling for block order, by using a repeated-measures ANOVA with the order of the blocks as the between-subject factor and block type (effort or reward) as the within-subject factor.

In addition, we assessed participants' ability to modulate effort exertion as a function of reward, by calculating effort as the average speed of button presses (number of presses per second) for the high reward/high effort trials and for the low reward/high effort trials across the whole task. We took the *difference* (effort speed for high rewards minus effort speed for low rewards) to be a measure of effort modulation, such that if the difference would be expected to be positive, indicating that participants exerted more effort for high rewards than for low rewards.

Visual inspection, using box-and-whisker plots, revealed several clear outliers in the difference between effort exertion for high and low rewards. Ten outliers that were +/- 2 SDs outside the mean were removed from further analysis. Then, to determine if participants exerted more effort for high rewards, as expected, we conducted a one-tailed, one-sample t-test comparing the distribution of effort differences to $\mu = 0$ (representing no difference in effort exertion for high and low rewards). Additionally, to examine whether the ability to modulate effort based on reward value is associated with symptoms, we performed partial correlation analyses between the effort speed difference and depression (controlling for block order) and anhedonia (controlling for depression scores with anhedonia items removed and block order).

As most variables violated the assumption of normality, we used the Spearman's method for all correlations. Analyses were corrected for multiple comparisons by applying the Benjamini-Hochberg (BH) method (Benjamini Y, 1995).

Computational modelling

Several Q-learning models were fit separately to the reward and effort block data. The models contained between two and four parameters, including learning rates (α), outcome sensitivity (ρ), temperature (τ), choice bias (φ, i.e. repeated item selection *independent of the outcome*) and choice bias decay (γ) for each block. We fit two versions of each model: one that only accounted for factual learning, and another that additionally integrated counterfactual learning (see Supplementary Materials).

Maximum likelihood estimation was used for model fitting and models were compared using Akaike's Information Criterion weights (Wagenmakers & Farrell, 2004). For the best-fitting model, data simulations were performed using the estimated participant parameters, and the simulated and actual data were compared for model validation (see Supplement for details).

Parameter values from the best fitting model were correlated with depression scores, and with anhedonia scores controlling for depression (with anhedonia items removed, as described above). Spearman's method was used as assumptions of normality were violated.

Results

Demographics and questionnaire measures

Table 1 describes subjects' demographics. Participants had a mean age of 19 years and a broad range of depression and anhedonia symptoms.

Characteristics	Mean (SD) or frequency. N = 155.
Age (years)	19.10 (1.98)
Gender Split (F/M/O)	118/32/5
Females (%)	76.13
Ethnicities (%)	
White	62.5
BAME	31
Other	6.4
Reward Learning (%)	68.93 (16.87)
Effort Learning (%)	70.71 (16.33)
BDI	15.9 (10.04)
SHAPS	2.19 (2.57)
TEPS Total	73.81 (10.01)
TEPS-A	41.1 (7.04)
TEPS-C	32.71 (4.76)

Table 1: BAME, Black, Asian and Minority Ethnic; BDI, Beck Depression Inventory; TEPS-A, Temporal experience of pleasure scale - anticipatory; TEPS-C, Temporal experience of pleasure scale - consummatory; SHAPS, Snaith-Hamilton Pleasure Scale.

Symptoms and subjective ratings

To assess potential habituation to the stimuli, we used a repeated-measures ANOVA and found no significant effects of rating (liking, wanting, effort willingness; $F(2, 924) = 1.02$, $p =$

.361) or time (pre or post task; $F(1, 924) = 0.05$, $p = .829$), and no significant interaction ($F(2, 924) = 0.51$, $p = .601$).

In addition, we examined the relationships between symptoms and subjective ratings of puppy images at the beginning of the task. We found that, as depression symptoms ($r = -0.194$, $p = .016$) and consummatory anhedonia (TEPS-C; $r = 0.194$, $p = .016$) increased, liking of puppy images decreased. Moreover, as anticipatory anhedonia (TEPS-A) increased, liking ($r = 0.308$, $p<0.001$), wanting ($r = 0.308$, $p<0.001$) and willingness to exert effort ($r=0.183$, $p = 0.023$) for puppy images decreased (Figure 2). After applying the BH method for multiple comparisons, the correlations for liking and wanting ratings remained significant (Tables S2 and S3).

Higher Anhedonia correlates with Lower Reward Liking, Reward Wanting, and Willingness to Exert Effort for Reward

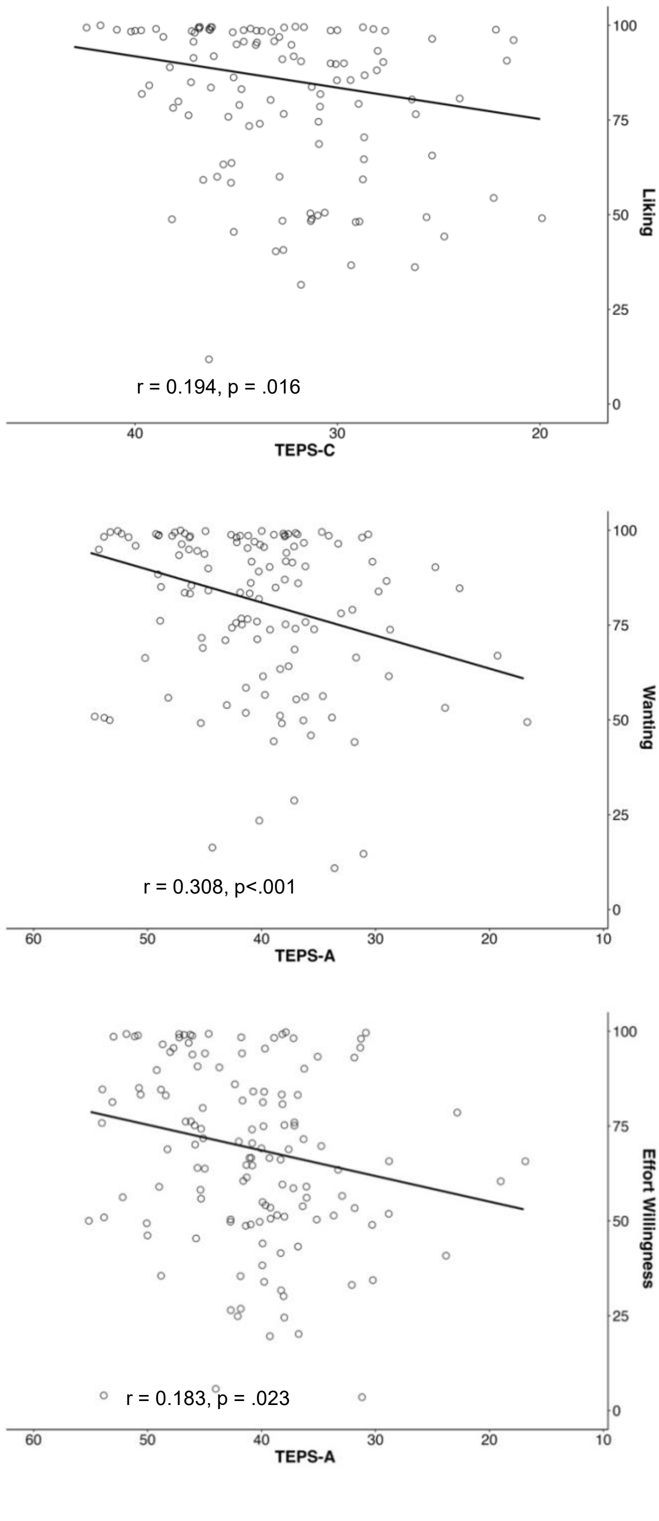

Figure 2: Subjective ratings plotted against anhedonia scores (higher TEPS = lower anhedonia).

Symptoms and Task Measures

We also examined if learning accuracies differed between effort and reward learning blocks, which revealed no significant main effect of learning type ($F(1,153) = 1.168$, $p = .281$) or of block order ($F(1,153) = 0.032$, $p = .859$) on learning accuracy, and no significant interaction ($F(1,153) = 0.752$, $p = .387$).

We found that, as depression symptoms increased, reward learning accuracy decreased ($r = -0.17$, $p = .03$). No significant relation was found for effort learning accuracy. As consummatory anhedonia increased (TEPS-C), reward learning ($r = 0.17$, $p = .035$) and effort learning accuracies ($r = 0.18$, $p = .03$) decreased (Figure 3). However, none of these findings survived correction for multiple comparisons (Figures S4 and S5). There were no significant relationships between learning accuracies and TEPS-A or SHAPS.

Regarding the ability to modulate effort exertion as a function of reward,. a one-sample t-test showed that the difference between effort exerted for high rewards vs low rewards across all participants was significantly greater than 0, indicating that the task was sensitive to effort modulation effects ($t(144) = 2.459$, $p = .008$). Additionally, as anticipatory anhedonia increased (lower TEPS-A), the difference between effort exerted for high vs low rewards was shown to decrease at trend level ($r = 0.11$, $p = .053$), suggesting a poorer ability to modulate effort based on reward in those with anhedonia symptoms. We found no significant relationship between effort modulation and depression symptoms.

Higher Consummatory Anhedonia correlates with Lower Reward and Effort Learning Accuracy

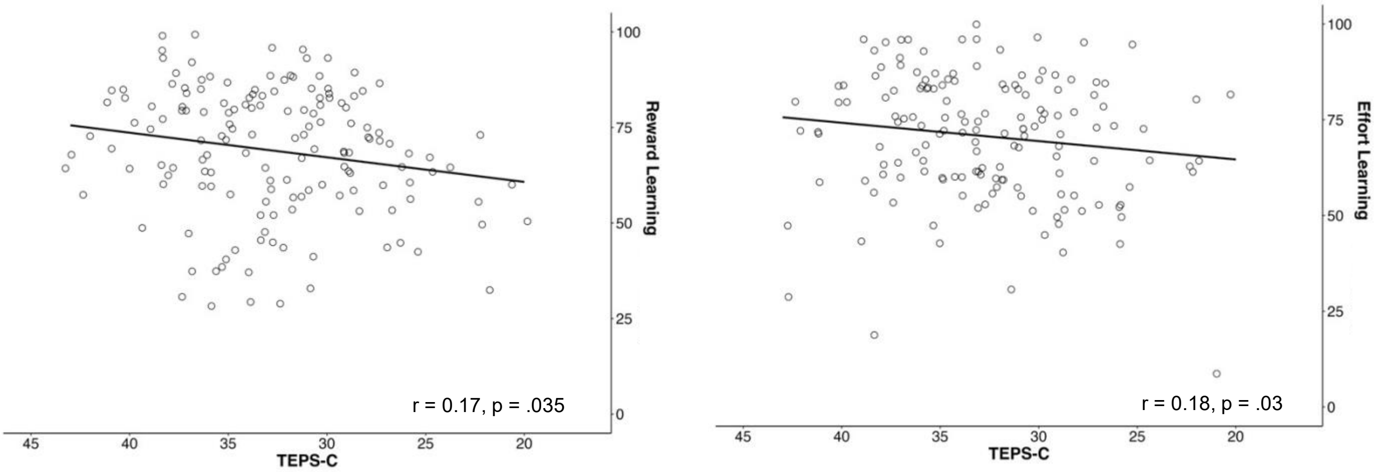

Figure 3: Reward and Effort learning accuracy plotted against consummatory anhedonia.

Computational modelling

For both reward and effort learning, the best fitting model included counterfactual learning, with only a learning rate and a temperature parameter (Table S1).

Examining correlations between learning rates, temperature parameters, and symptoms, we found that, as depression scores increased, temperature values for reward learning increased at trend level ($r = 0.146$, $p = .07$). Moreover, as consummatory anhedonia increased, temperature values for reward learning (TEPS-C; $r = -0.163$, $p = .043$) and effort learning (SHAPS; $r = 0.159$, $p = .049$) increased as well. However, these results did not survive multiple comparison corrections (Tables S6 and 7). No significant relationships were found between the learning rates and symptoms.

Discussion

The main aim of this study was to examine the relationships between depression and anhedonia symptoms, and reward and effort learning in young people.

Firstly, when examining subjective responses, we found anticipatory anhedonia was associated with reduced wanting and liking of reward, consistent with findings from our previous study also using puppy image rewards (Frey et al., 2023a). We also observed that anticipatory anhedonia was associated with reduced willingness to exert effort for reward. This is in line with findings in depression of reduced exertion of grip force for monetary rewards (Clery-Melin et al., 2011) and reduced choices of high effort/high monetary reward options (Horne et al., 2021), but extends these previous results by demonstrating reduced subjective willingness to exert effort for primary rewards in anhedonia. In addition, we showed that lower reward liking was associated with consummatory anhedonia and depression symptoms. As consummatory anhedonia was only significantly linked to liking and not wanting of the rewards, this supports the notion that reward sub-processes are subjectively dissociable (Treadway & Zald, 2011).

When examining the task data, we found greater effort exertion for high rewards compared to low rewards, as expected, indicating that the task is sensitive to reward-based effort modulation effects. Moreover, participants' learning performance was similar for the reward and effort learning blocks, in line with our expectations that using a block design would remove the trade-off between effort and reward learning.

We also found that, as anticipatory anhedonia increased, the difference between the effort exerted for high vs low rewards decreased, idicating that individuals with anhedonia exerted similar effort for high and low rewards. This finding is in line with previous studies showing that depressed individuals fail to exert more effort for higher or more likely rewards (Horne et al., 2021), but we extend this further by showing that effort modulation is impaired in anhedonia. Our results are also consistent with research in schizophrenia using effort-based decision making tasks which have found that anhedonia is associated with an inefficient effort pattern when trading potential benefits against the associated costs (Fervaha et al., 2013; Ince Guliyev et al., 2022; McCarthy et al., 2016; McCarthy et al., 2015). Our results extend these findings by showing, to our knowledge for the first time, that anticipatory anhedonia is associated with poorer modulation of effort as a function of reward in young people with depression symptoms.

Further, we demonstrated that, as depression symptoms increased, reward learning accuracy decreased (i.e. the side that leads to high rewards was chosen less frequently), which is consistent with findings of blunted reward response biases in depression (Esfand et al., 2024; Pechtel et al., 2013; Pizzagalli et al., 2008; Pizzagalli et al., 2005; Vrieze et al., 2013). We also found that, as consummatory anhedonia increased, reward learning accuracies decreased, which is similar to our previous findings (Frey et al., 2023a) and in line with studies showing blunted reward response biases with increasing anhedonia (Q. J. Huys et al., 2013; Kangas et al., 2022; Liu et al., 2016; Vrieze et al., 2013). We extended these findings by also demonstrating, for the first time to our knowledge, an association between consummatory anhedonia and decreased *effort* learning accuracies. This suggests that difficulties with learning to avoid aversive situations in real life could result in lower in-the-moment enjoyment. However, as these results did not survive corrections for multiple comparisons, future studies with larger sample sizes are needed to further support these findings.

Using computational modelling, we found that, as consummatory anhedonia increased, temperature values increased for both reward and effort learning. This is consistent with the observation of impaired choice behaviours in reward learning in depression (Kunisato et al., 2012; Lloyd et al., 2024; Rupprechter et al., 2018), and a meta-analysis showing more variable choices in anhedonic, depressed and bipolar individuals in a probabilistic reward task (Q. J. M. Huys et al., 2013). However, we have extended these findings by showing, for the first time, that consummatory anhedonia also correlates with increased temperature during effort learning. This novel finding could explain the lower reward and effort learning accuracies with increasing consummatory anhedonia observed in this study, as anhedonic individuals under-exploit higher-valued choices.

As the association between temperature and consummatory anhedonia did not survive correction for multiple comparisons, future studies with larger sample sizes are needed to confirm this relationship. Further, a mostly female sample limits the generalizability of our findings, so future studies may broaden recruitment to include males. In addition, recruiting beyond university students would help assess the influence of education and socio-economic status on reward and effort learning.

Though this link requires further examination, our findings suggest that addressing biases in exploration/exploitation behaviour could be a target for novel intervention development to help improve the everyday lives of those living with depression and anhedonia.

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4.2. Supplementary Materials

Supplementary Methods

Computational Modelling

Q-learning models were fit separately to the reward and effort learning data. The Q-values, which represent the predicted outcome value of a given item choice, were initialised at 0.5 for reward learning and at -0.5 for effort learning, as subjects were informed of the aim, i.e. maximize reward or minimize effort, in a 'hint' page at the start of each block. Q values were updated on each trial (t) for the selected item (A) as follows:

$$Q_A(t+1) = Q_A(t) + \alpha(\rho R(t) - Q_A(t))$$

where α is the learning rate and ρ is the outcome sensitivity. The outcome value, R(t), was set to 0 and 1 for low and high rewards in the reward learning block, respectively, and to 0 and -1 for low and high effort in the effort learning block, respectively.

In the models that included counterfactual learning (or double-updates), the Q-value of the non-selected item (B) was also updated using the *inverse* of the outcome of the chosen side, R'(t):

$$Q_B(t+1) = Q_B(t) + \alpha(\rho R'(t) - Q_B(t))$$

A SoftMax function was used to determine the probability of participants' choices (of item A over B) under the model on each trial:

$$P_A(t) = \frac{e^{\frac{Q_A(t) + \varphi * c_A(t)}{\tau}}}{e^{\frac{Q_A(t) + \varphi * c_A(t)}{\tau}} + e^{\frac{Q_B(t) + \varphi * c_B(t)}{\tau}}}$$

where τ is the temperature parameter, $c_A(t)$ is an indicator variable whose value depends on whether item A was chosen on the previous trial ($c_A(t)$ = 1) or not ($c_A(t) = \gamma * c_A(t-1)$; γ is a decay parameter), and φ is a choice bias parameter indicating the likelihood of repeated item choices *independent of their outcomes* (i.e., "sticky choice"; (Schönberg et al., 2007)).

Models contained different combinations of the learning rate, bias, outcome sensitivity, and the temperature parameters (α, τ, γ, ρ, φ; Table S1).

Each model was fit separately to the reward and effort learning data for each participant by maximising the log likelihood estimate (LLE) of the participant's choices under the model across all trials within a given block, thus maximising:

$$LLE = ln\left(\prod_t P_{i,t}\right)$$

The relative fit of the different models was compared using Akaike's Information Criterion (AIC) weights (Wagenmakers & Farrell, 2004).

The fit of the best model was then compared to chance using *pseudo-R^2* values (as in (Frank et al., 2007)), comparing the LLE of the learning model to the LLE of the null model, in which $P_A(t)$ is set to 0.5 for each trial. The data of 14 subjects for reward learning and 7 for effort learning demonstrated a better fit to the null model than to the learning model.

For model validation, data simulations using the estimated parameter values from the best fitting model were conducted. For each participant's parameter values, 25 simulations were run per block. The accuracy (i.e. whether or not the item with the higher probability of yielding high rewards or low effort was selected) across all trials was determined for each simulation, and the accuracies averaged across the 25 simulations were recorded as the simulated reward and effort learning accuracy of each participant. The simulated accuracy data was then compared, graphically, to the actual data to assess how well the estimated parameters are able to capture the patterns observed in the actual data (Figures S1 and 2). Outputs were examined across all subjects and for only those subjects whose data fit better to the learning than to the null model.

Model	**α**	**γ**	**φ**	**ρ**	**τ**	**Update**	**AIC weights reward**	**AIC weights effort**
1	X				X	factual	0.245	0.267
2	**X**				**X**	**counterfactual**	**0.509**	**0.494**
3	X			X	X	factual	0.016	0.005
4	X			X	X	counterfactual	0.098	0.075
5	X	X			X	factual	0.032	0.029
6	X	X			X	counterfactual	0.065	0.107
7	X		X		X	factual	0.009	0.008
8	X		X		X	counterfactual	0.01	0.009
9	X	X	X		X	factual	0.005	0.002
10	X	X	X		X	counterfactual	0.01	0.004

Table S1: Akaike's Information Criterion (AIC) weights indicate the relative fit of different models, with higher weights representing a better fit. Model 2 shows the best fit to both reward and effort learning data. 'Update' refers to whether only factual outcomes, or factual and counterfactual outcomes, were used to update the Q-values.

Supplementary Results

Symptoms and Subjective Ratings

As reported in the main paper, we used Spearman's correlations to examine the association between subjective reward ratings and anhedonia and depression symptoms. By applying the Benjamini-Hochberg (BH) method (Benjamini Y, 1995), we corrected for multiple comparisons within each rating type for anhedonia (Table S2), and across the three ratings for BDI (Table S3).

Symptoms	Liking	Wanting	Willingness To Exert Effort
TEPS-A	<.001	<.001	.069
TEPS-C	.024	.126	.086
SHAPS	.073	.271	.477

Table S2: P-values corrected for multiple comparisons per rating type, using the BH method, for partial Spearman's correlations controlled for BDI (anhedonia items removed).

	Corrected p's
Liking	.048
Wanting	.107
Willingness To Exert Effort	.158

Table S3: BDI correlations with each rating corrected for multiple comparisons using the BH method.

In addition, we conducted Spearman's partial correlations, controlling for BDI (anhedonia items removed), between anhedonia symptoms and learning accuracies (Table S4), as well as full correlations between BDI (full scale) and learning accuracies (Table S5). The below tables report the p-values corrected by applying the BH method for multiple comparisons.

Symptoms	**Reward Learning**	**Effort Learning**
TEPS-A	.925	.537
TEPS-C	.111	.081
SHAPS	.925	.086

Table S4: P-values corrected for multiple comparisons for reward and effort learning accuracies, using the BH method, for partial Spearman's correlations controlled for BDI (anhedonia items removed).

	Corrected p's
Reward Learning	.060
Effort Learning	.150

Table S5: BDI correlations with reward and effort learning accuracies corrected for multiple comparisons using the BH method.

Symptoms and Parameters

As we found significant results for reward and effort learning temperature parameters (τ), we report below the corrected p-values using the BH method for comparisons with anhedonia (Table S6) and depression (Table S7) symptoms.

Symptoms	Reward τ	Effort τ
TEPS-A	.503	.645
TEPS-C	.129	.128
SHAPS	.503	.128

Table S6: P-values corrected for multiple comparisons for reward and effort learning temperature parameters, using the BH method, for partial Spearman's correlations controlled for BDI (anhedonia items removed).

	Corrected p's
Reward τ	.140
Effort τ	.618

Table S7: BDI correlations with reward and effort learning accuracies corrected for multiple comparisons using the BH method.

Model Validation

Model 2, which contained only a learning rate and a temperature parameter and utilised counterfactual outcome information, showed the best fit for both the reward and effort learning data. For model validation, we ran 25 simulations using the parameter estimates of model 2. Although the overall accuracies were slightly underestimated, the relative accuracy pattern of the simulated data resembled that of the real data in the whole sample (Figure S1) and after the removal of participants whose data fit the null model better than the learning model (Figure S2). Additionally, the *pseudo-*R^2 values for the whole sample indicated that, in both reward (*pseudo-*R^2 = 0.28) and effort (*pseudo-*R^2 = 0.32) learning blocks, the model provided a relatively good fit for the data.

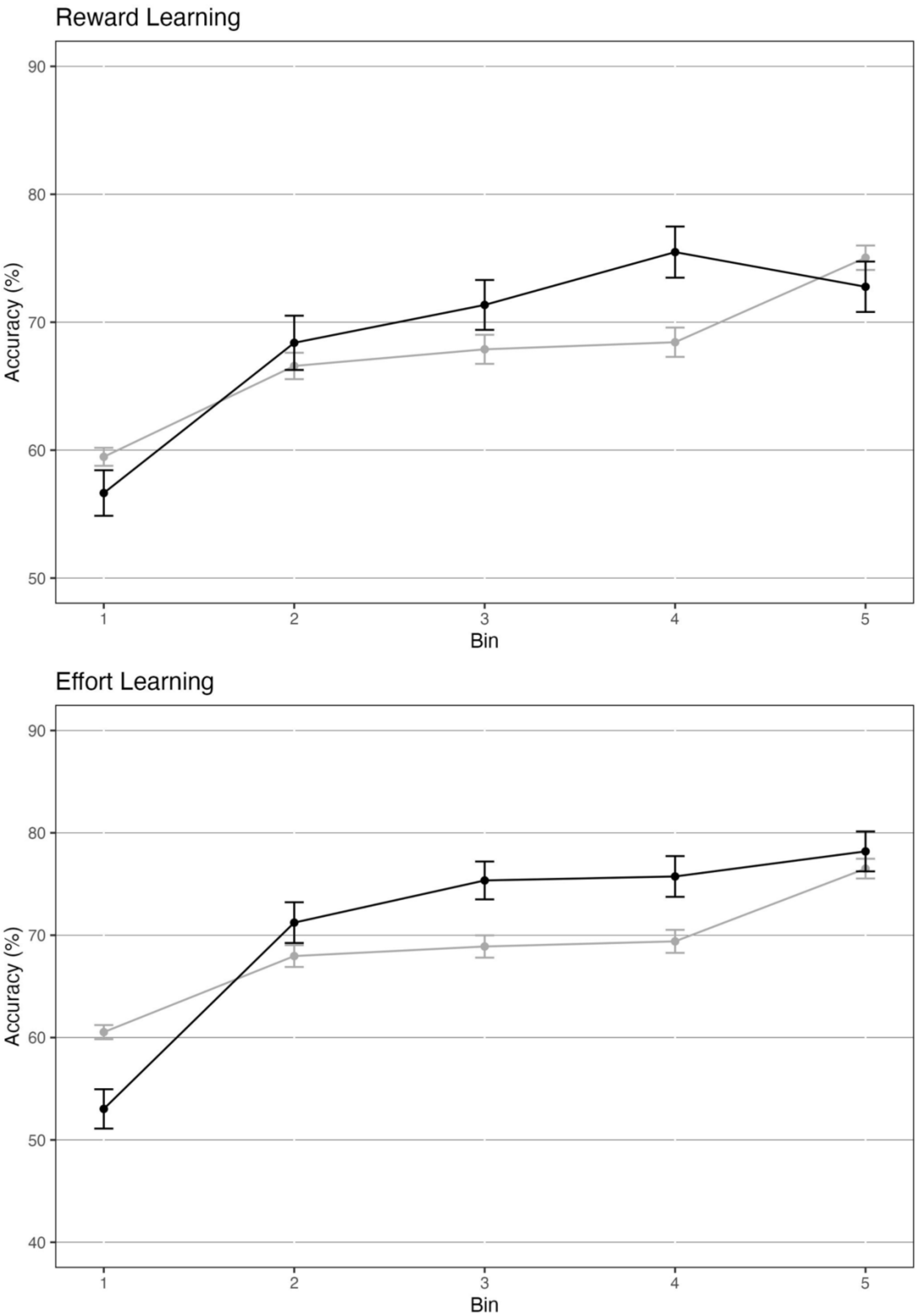
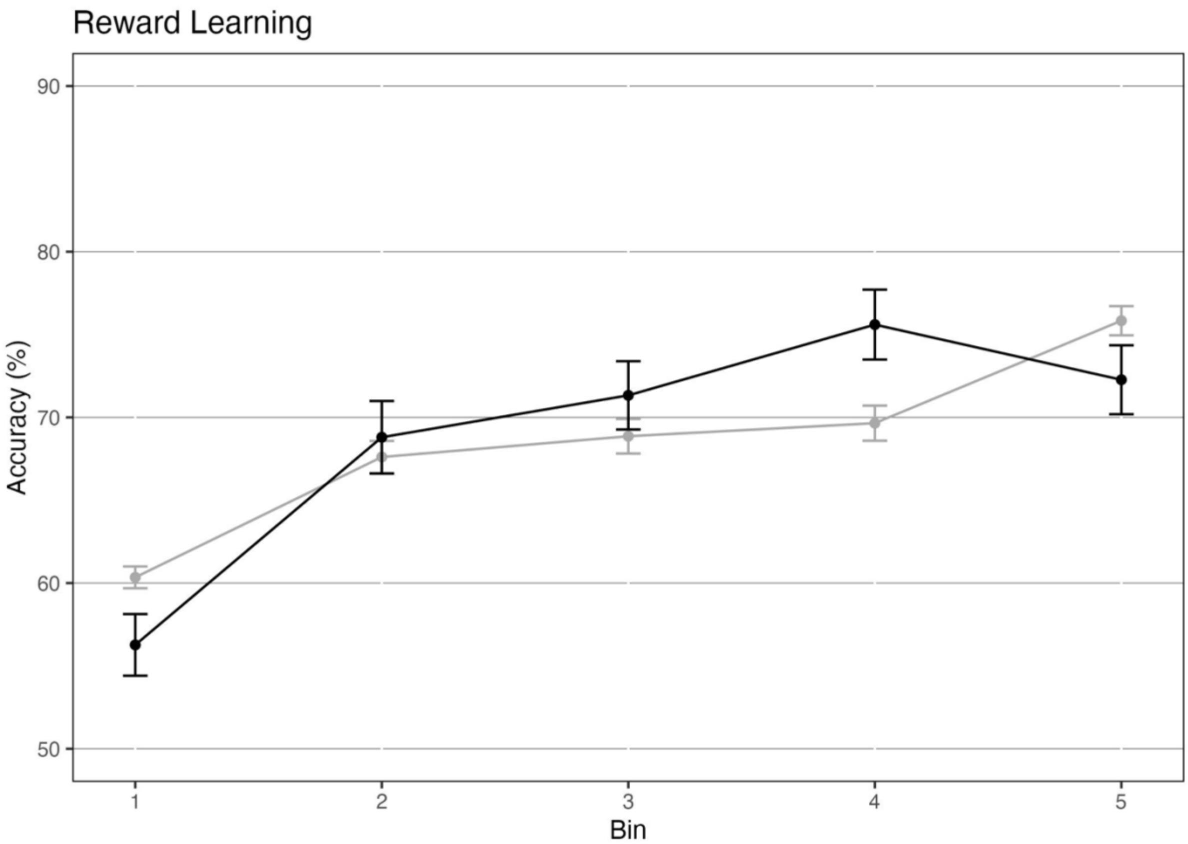


Figure S1: Actual (black) and simulated (grey) accuracies across all participants (N = 155), using parameter estimates from the best fitting model.



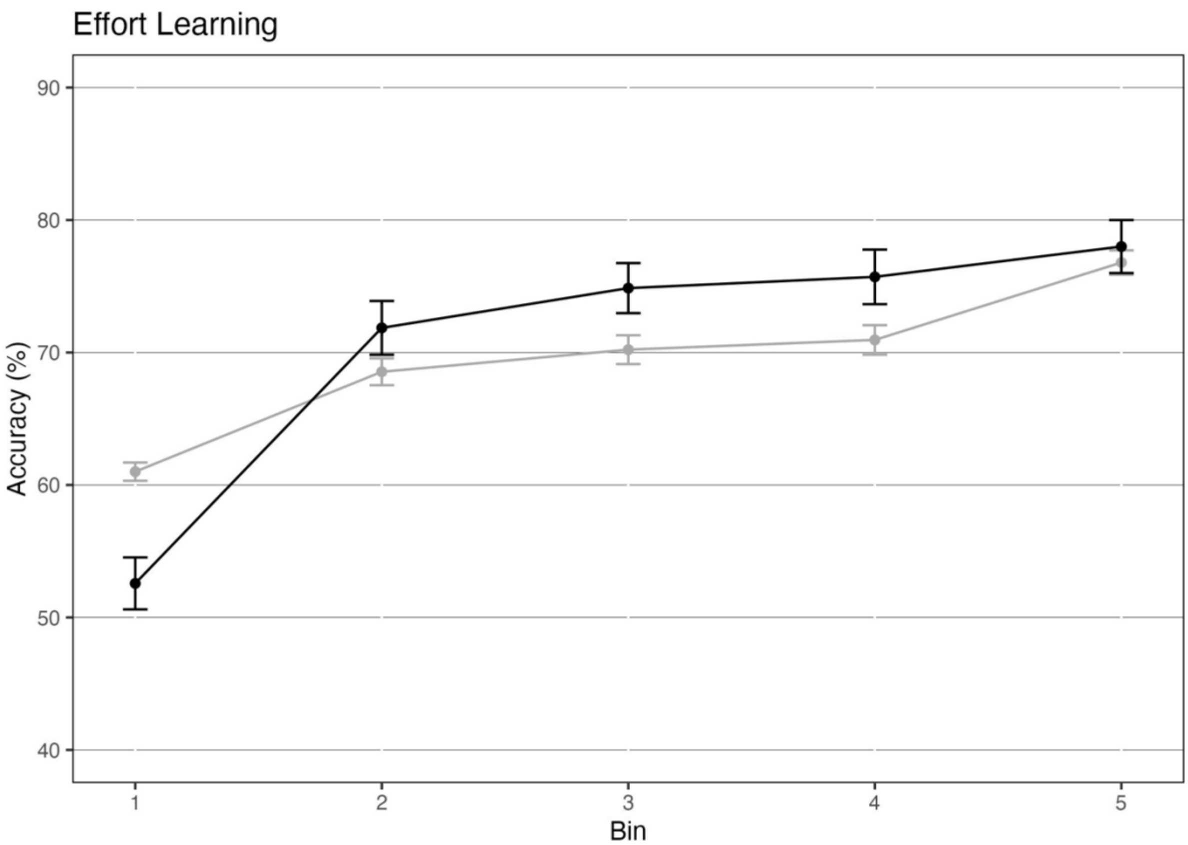


Figure S2: Actual (black) and simulated (grey) accuracies after removing participants whose data fit the null model better than the learning model (reward learning n removed = 14; effort learning n removed = 7), using parameter estimates from the best fitting model.

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5. General Discussion

This section has summarised the methodologies used in the studies and the most important findings. Their strengths and limitations have been evaluated, and suggestions for future research has been discussed.

With the rapidly growing field of 'healthtech' and growing awareness of mental health issues amongst young people, novel ecological momentary interventions (EMI) are considered the next 'big thing' to revolutionise healthcare. EMIs utilise various methods, such as personalised feedback (Bastiaansen et al., 2018) or chatbots (Heinz et al., 2025), that are optimised to maintain high efficacy, compliance and acceptability of EMIs amongst young people. A recent review of digital interventions in 16-25 years olds has shown that cognitive behavioural therapy (CBT) has been the most commonly studied EMI, primarily using apps that combine digital intervention with human support (Potts et al., 2025). The purpose of the research in this thesis has been to support the development of future digital interventions. Therefore, this section has identified and evaluated, where possible, potential interventions that the critical findings from this thesis would support.

5.1. Paper 1: Targeting Enjoyment & Behaviour

5.1.1. Methodology & Findings

Paper 1 adapted the EMA questionnaire and procedure from Edwards et al. (2018), assessing the reward processing sub-components anticipation (anticipatory pleasure, expectation) and motivation (interest, preference) of upcoming events, and the consummatory pleasure of current events, in 7 assessments per day for 6 days (further details in Paper 1, Methods). Participants chose from a list of physical activities that were then categorised into leisure (relaxing, other leisure activities, exercising) and functional (work/school, hygiene, etc.), for analysis. They also chose from a list of social activities which were then categorised into social (friends, family, partner) and non-social (alone) for analysis. With baseline measures of depression symptoms using the MFQ (Mood and Feelings Questionnaire), Paper 1 was able to examine the relationship between depression severity, and real-life moment-to-moment experiences of reward processing, and time spent in individual physical activities and company. These were modelled using multiple linear regression.

Further, Paper 1 utilised the moment-to-moment assessments in EMA, to examine the predictive relationships between reward processing sub-components and behaviour, between consecutive assessments. These time-lagged relationships were modelled using multilevel linear and logistic regression accounting for subject-level random intercepts. In the logistic models, the outcomes were engagement in physical activities (0 = functional, 1 = leisure) or company (0 = non-social, 1 = social), while the linear models assessed the predictors of enjoyment of physical activities and company. These models were separately conducted in groups based on depression severity: high (HD, MFQ ≥ 27, N=48), moderate (MD, MFQ 16–27, N=16), and low, i.e. controls (C, MFQ ≤ 16, N=22). The main findings will be discussed alongside how these findings could help inform the development of interventions.

A general finding was that higher depression symptoms predicted lower anticipation, motivation and enjoyment, associated with both leisure activities and social company. This is consistent with deficits in real-life reward processing in group-based comparisons between depressed and controls (Li et al., 2019; Wu et al., 2017). The self-reported findings from Paper 1 of more time doing “nothing” at higher depression symptoms confirms the objective findings of less physical activity from wearable watches in depression (Gianfredi et al., 2020; Schuch et al., 2017). Further, Paper 1 showed that less time was spent in hygiene at higher depression symptoms, which perhaps reflects the findings of greater self-neglect predicting a greater risk of depression (Ranasinghe et al., 2016). Likewise, we found that spending less time doing work/school was associated with higher depression symptoms in Paper 1 which might relate to the often-observed academic underachievement in depression (Duncan et al., 2021; Fergusson & Woodward, 2002). Overall, these results are consistent with depression research and validate the deficits in reward processing and behavioural patterns associated with depression.

The critical findings of Paper 1 came from the time-lagged analyses. One important finding was that higher anticipatory pleasure predicted greater future enjoyment of both physical activities and company in the high depression group, especially when the anticipated and actual activities are the same. This additionally demonstrated that anticipatory pleasure could be the unique predictor of future enjoyment, instead of motivation (interest, preference), in those with depression. This was not assessed in previous studies as they didn't measure motivation (Bakker et al., 2017; Li et al., 2019). Another critical finding was that higher anticipatory pleasure predicted greater engagement in leisure activities and social company, specifically if the anticipated and actual activities were the same, in individuals with higher depression symptoms. These findings suggest the important role of the pleasure individuals anticipate having in future events in driving them to subsequently engage in it and enjoy it.

5.1.2. Strengths

Paper 1 went beyond prior EMA research with novel analyses to reveal new insights. Li et al. (2019) had identified that time-lagged analyses were yet to be done for anticipation and enjoyment of the *same* events, suggesting that their models demonstrated that greater anticipatory pleasure for any planned activity predicts greater enjoyment of any future activity. Paper 1 made best use of the rich intensive longitudinal data by matching contexts (physical activities and company) between consecutive assessments, allowing the study to examine if the anticipation of activity 'A' predicts the enjoyment of activity 'A' at the next assessment.

Unlike previous studies that conducted time-lagged analyses (Bakker et al., 2017; Li et al., 2019), Paper 1 included predictors other than just anticipatory pleasure. These were expectation and motivation (interest, preference), which allowed Paper 1 to examine if sub-components other than anticipatory pleasure were stronger predictors of outcomes. The study also included positive affect (PA), negative affect (NA) and assessment time (order of assessment during the day, recorded as 1-7, as a measure of the time of day) as co-variates in all multilevel models, given they had confounding effects, as reported in the Supplementary Results.

Last, Paper 1 was the first study, as far as is known, to examine how reward sub-components drive future engagement in leisure activities and social company. As leisure activities (Bone et al., 2022; Chen et al., 2012; Harvey et al., 2010; Lin et al., 2008; Mikkelsen et al., 2010) and social company (Campbell et al., 2022; Panaite et al., 2021; Pemberton & Tyszkiewicz, 2016) can protect against depression symptoms, interventions that target sub-components to increase engagement in such activities could provide the basis for reward-based interventions.

5.1.3. Limitations & Future Directions

Despite these strengths of Paper 1 that provided many novel insights, some limitations must be considered when interpreting its findings, which need to be addressed in future research. Firstly, the sample of Paper 1 was mostly highly educated young females, so its findings cannot be generalized to all young people. Although we examined the data with gender as a confound, actively recruiting males could allow future studies to directly examine gender-based differences in reward processing in young people.

Second, the EMA questionnaire did not assess motivation (interest, preference) and expectation related to social contexts, so the only predictor in the 'company' models was anticipatory pleasure. Therefore, while Paper 1 demonstrated that anticipatory pleasure uniquely predicts enjoyment and engagement in physical activities, such a claim cannot be made for social contexts. Adding questions on motivation and expectation regarding social contexts would be the next step in EMA studies investigating time-lagged relationships. Another limitation in interpreting these findings is that Paper 1 is the first study to utilise certain analyses, so findings cannot be evaluated against prior research. Therefore, it is important to replicate the findings of Paper 1 as it is the first study to examine the relationship between the appetitive (anticipation, motivation) and consummatory (enjoyment) sub-components of reward processing, and behaviour. It was the first to show the predictive capacity of anticipatory pleasure, rather than motivation, in depressed individuals, specifically when the anticipated and actual activities were the same. Paper 1 was also the first to utilise such analyses of matching contexts (activities, company) between consecutive assessments, thereby requiring more studies to validate these findings.

Further, as participants often did not do what they planned on doing in the previous assessment, there was a large amount of data loss after contexts were matched between consecutive assessments. Going forward, future studies should collect more daily assessments in each participant, such that more matched time-lagged relationships can be captured. This, however, needs to be balanced against the burden that frequently answering questionnaires would have on participants. The current protocol of 7 assessments a day was rated by participants as having no significant effect on their mood, daily activities or contact with other people (Table S2; Paper 1, Supplementary Materials), so potentially more assessments could be added that may not disrupt daily life. As other EMA studies have adopted upto 10 assessments a day (Ernst et al., 2022; Stone et al., 2021), this could be applied in future EMA studies examining time-lagged relationships in depression.

In the current EMA questionnaire the measure of ‘expectation’ (what do you think are the chances this activity will occur?) is difficult to interpret. Edwards et al. (2018) argued that this question measures the cognitive aspect of anticipation, with anticipatory pleasure accounting for the affective aspect. However, an individual may interpret it as a compound measure of their ability to plan an activity and the chances that other people will cancel plans. As the latter factor is beyond an individual’s control, this thesis proposes that a more appropriate measure should be used in future studies. Self-efficacy is just such a measure, which captures the self-reported confidence in one’s ability to execute behaviours (Waddington, 2023), such as making friends (social domain) (Muris, 2001) or exercising (physical activity domain) (Resnick & Jenkins, 2000). Deficits in self-efficacy have been demonstrated in adolescents with depression symptoms across academic, emotional and social domains (Fürtjes et al., 2023; Tak et al., 2017), but the predictive capacity of self-efficacy for enjoyment and engagement in activities is yet to be explored in depression.

The assessments used only self-report questionnaires, recording the physical and social contexts individuals were in. New methodologies that passively record data using smartphones, such as global positioning system (GPS) to examine location and movement, and microphones to assess ambient noise, are fast becoming a part of mental health research (Torous et al., 2021), which limit the burden on individuals while also providing extremely rich data. This has been used to assess social impairment in schizophrenia (Fulford et al., 2021; Wang et al., 2020), for example ambient noise to assess duration of conversations, smartphone usage to examine how frequently individuals used social networking apps, and GPS to determine which locations individuals were in throughout the day. While Paper 1 was only able to assess the company individuals were in, these passive sensing techniques could provide more details about these interactions. Therefore, integrating self-report questions (enjoyment, anticipation) with passive sensing (locations, ambient noise) in future studies could allow researchers to examine novel relationships and how they are moderated by depression symptoms. Further, as adolescents and young adults are hypersensitive to approval and rejection from peers (Altikulaç et al., 2019; Flores et al., 2018; Foulkes & Blakemore, 2016), examining how they process social interactions could reveal methods to prevent potentially detrimental effects on mood and behaviour.

5.1.4. Episodic Future Thinking as a Potential Intervention

An intervention that can potentially exploit the predictive relationship between reward processes is Episodic Future Thinking (EFT; Schacter et al., 2008). This is a cognitive exercise in prospection, where individuals are required to imagine positive future events that they anticipate engaging in, and describe in detail the feelings, thoughts, context and actions related to the forthcoming activities, thereby directly targeting the experience of anticipatory pleasure. Future Specificity Training (FeST), where subjects practised *adding* specificity (detailing contextual aspects, like time and place, of future activities) to stress the importance of spatiotemporal context in future thinking, demonstrated greater improvements in anticipatory pleasure in healthy controls that underwent training compared to waiting-list subjects (Hallford, Yeow, et al., 2020). FeST is also shown to be effective in MDD subjects, as Hallford et al. (2023) demonstrated elevated anticipatory pleasure in the FeST intervention group vs the non-FeST group. It also appears to improve real-life momentary experiences, as pre and post intervention comparisons in a small sample of MDD adults using EMA show within-subject increases in vividness, specificity and anticipatory pleasure for future events (Hallford, Sharma, et al., 2020). Therefore, by exploiting the predictive relationship between anticipatory pleasure and future enjoyment and engagement, FeST-induced increases in pleasure anticipated from future events could be an effective intervention.

There is, however, evidence that suggests limited effectiveness of EFT. Examining the effects of mental imagery (MI, similar to EFT) in individuals with depression symptoms on momentary experiences using EMA, Bär et al. (2024) reported increases in motivation and anticipatory pleasure, as expected, but not active behaviour (actively engaged or approaching something). Interesting, the use of MI had no impact on the temporal relationship between anticipatory pleasure (t-1) and active behaviour (t), implying that EFT interventions may have limited impact of behaviour. Note, that this is only one study, so it remains inconclusive.

As such, EFT's effectiveness in increasing enjoyment and engagement in leisure and social company remains speculative as this has not yet been *directly* examined. Future studies could incorporate EFT as an ecological momentary interventions (EMI), delivering cues to elicit vivid mental imagery using written and audio prompts (Persson et al., 2024) or AI-based chatbots like EFTeacher (Ahmadi et al., 2025). From literature, EFT-based digital interventions appear to be in their nascent stages, but may be an effective intervention. Therefore, many avenues of research can be explored in the future.

5.2. Paper 2: The Mood Brightening Effect

5.2.1. Methodology & Findings

Paper 2 investigated the mechanisms that underpin the mood brightening (MB) effect of leisure activities (relaxing, other leisure, exercising) and social company (friends, partner, family). This is the phenomenon where a greater elevation of mood in response to positive activities, i.e. elevated PA, reduced NA or both, is observed in depressed individuals compared to healthy controls (for example: Bylsma et al., 2011; Khazanov et al., 2019). This was an extensive study, utilising robust modelling and many combined methodologies in the same study. It investigated reactivity to actual activities, instead of subjectively rated ‘positive’ activities, which has only previously been done in two studies (Heininga et al., 2019; van Loo et al., 2023).

Paper 2 measured reactivity as the *change* in momentary affect from two different baselines, that have been separately used in other studies: affect at the previous assessment (or, at t-1) (Khazanov et al., 2019; Thompson et al., 2012) and within-subject mean affect (Bylsma et al., 2011). With mean affect as baseline, reactivity represented how engaging in activities changes momentary NA and PA from an individual’s “general” experience. With affect (t-1) as baseline, the results provide a measure of “temporal instability” of affect, i.e. change in affect between consecutive assessments (Koval et al., 2013). The multilevel linear regression models in this study controlled for the baselines, age and gender.

The main finding of this study was that NA reactivity underpins the MB effect of leisure activities and social company. Paper 2 found that the *increase* in NA, relative to affect (t-1), was *dampened* when those with higher depression symptoms were engaged in leisure activities compared to functional activities. This shows engagement in leisure activities more effectively reduces the temporal instability of NA in depressed individuals. Similarly, when using the mean affect as the baseline, a *larger decrease* in NA was observed in those with higher depression symptoms, when engaged in leisure activities and social company.

In the context of previous research, van Loo et al. (2023) was the only other study to also investigate this, and showed that NA reactivity underlies the MB effect of being physically active and socialising, but that PA reactivity is additionally involved when socialising. Thus, the findings from Paper 2 may validate the phenomenon that NA reactivity consistently underlies the MB effect. Overall, this suggests that, at higher depression symptoms, reducing or stabilising negative emotions could effectively elevate mood from leisure activities and social company. Thus, the study would conclude that re-orienting individuals to value reducing negative emotions, which is in line with a previous study that made similar observations (Panaite et al., 2019). This may maintain long-term engagement in these activities in depressed individuals. However, as studies comparing NA and PA reactivity to real-life contexts are scarce, this study requires replication.

Further, previous studies have shown that greater NA instability predicts higher depression symptoms (Bowen et al., 2013; Sultson et al., 2024; Thompson et al., 2012) and greater suicidal ideation (Jeong et al., 2021). The findings from Paper 2 suggest that engaging in leisure activities would stabilise negative emotions, which may be the mechanism that underlies the well-established protective effects of leisure activities against depression symptoms (Bone et al., 2022; Chen et al., 2012; Harvey et al., 2010; Lin et al., 2008; Mikkelsen et al., 2010). However, as Paper 2 is the first known study to examine the effects of context on temporal instability, replication is needed.

As the core symptom of depression is anhedonia, associated with blunted PA, NA might be the only aspect of mood that is able to react to real-life activities (leisure or social company) in depressed individuals. This may explain the central role of NA in driving the MB effect in Paper 2.

Further, van Loo et al. (2023) reported that PA was elevated in social company, in addition to suppressing NA, in those with higher depression symptoms. They argue that, as socialising is shown to have positive effects, i.e. elevating self-esteem (Denissen et al., 2008) and distracting from ruminative thinking (Puterman et al., 2010), being in social company is likely to increase positive emotions. In contrast, Paper 2 reported that NA was reduced (vs. mean NA) in social company in individuals with higher depression symptoms. As van Loo et al. (2023) and Paper 2 are the only two studies to have examined reactivity to actual activities, replication of these studies is required to confirm what drives the MB effect.

5.2.2. Strengths

A major strength of this study is that it investigated reactivity to actual activities, instead of subjectively rated ‘positive’ activities, which has only previously been done in two studies (Heininga et al., 2019; van Loo et al., 2023). Subjectively rating events could be confounded by negative biases in depression where patients tend to put greater weight on negative experiences compared to positive experiences (Khazanov et al., 2019). Therefore, measuring reactivity in actual activities is more objective.

Paper 2 included 'relaxation' as an activity in the leisure category, which only contained physical exercise and being outdoors in a van Loo et al. (2023). This allowed Paper 2 to assess reactivity to a positive activity that young people spent ~30% of their time engaged in (Figure S1, Paper 2 Supplementary Results). Further, while Heininga et al. (2019) categorised social company and leisure activities in the same category (i.e. sports, hobby with friends, partner), Paper 2 and van Loo et al. (2023) have been the only studies to investigate reactivity of PA and NA to physical activities and company *separately*.

The most commonly used measure for temporal instability in previous studies was Mean Successive Squared Difference (MSSD; Jahng et al., 2008), which captured the average magnitude of change in affect between consecutive assessments. MSSD does not allow researchers to examine the effects of context on instability, as it collapses momentary data into a subject-level average measure of instability. Dejonckheere et al. (2019) had identified this as a gap in research. Using affect (t-1) as a baseline in Paper 2 has addressed this issue, as it allows for within-subject investigation of how the current context influences the change in NA and PA from the previous assessment. This appears to be a novel development in reactivity research.

Lastly, a major strength of Paper 2 was its robust analysis that took many precautions that previous studies did not. For example, Mestdagh et al. (2018) argued that the high NA levels and low PA levels, observed in depression (Bakker et al., 2017; Li et al., 2019; Wu et al., 2017), lie at the extreme ends of the measurement scales which restricts the fluctuations that may be recorded. Therefore, the models in this study controlled for mean affect - a measure of where an individual's affect lies on the measurement scale. Further, affective inertia, a subject-level measure of the moment-to-moment predictability of affect (Dejonckheere et al., 2019), may influence reactivity independent of the activity being engaged in. In other words, NA at 't-1' may strongly influence NA at 't', while the activity at 't' may not be responsible for the change in NA. Therefore, models controlling for inertia were also included in Paper 2.

5.2.3. Limitations & Future Directions

The use of affect (t-1) to measure reactivity is especially important to replicate, as it investigates the effect of real-life contexts on temporal instability of affect. A limitation, however, is the number of activity categories to select from. This especially applies to the category of 'other leisure activities' that was presented in this study. It is far too broad to provide any meaningful insight, as it leaves the interpretation of the term 'leisure' to the participant. Providing specific categories, such as 'playing video games' and 'sports', or allowing participants to fill out the activity they are engaged in would help mitigate this issue.

Future studies could also focus on activities that young people more commonly engage in, such as social media usage. Li et al. (2024) showed that broadcasting on social media (or active use) encouraged greater use of functional emotional regulation strategies than browsing (passive use), suggesting that affect may react to active and passive use differently. More time spent on social media is also shown to increase the risk of depression in adolescents (Liu et al., 2022). To further examine this, EMA studies could incorporate passive monitoring on smartphones to assess the frequency and duration of use of social media apps (Torous et al., 2021), and integrate with self-report questionnaires asking if the use was passive or active, and momentary NA and PA. This would help examine affective reactivity to the frequency, duration and type of social media use, and how depression and anhedonia symptoms moderate this relationship.

This thesis also recommends that future studies should conduct group-based comparisons of reactivity while including sub-threshold depression groups, in addition to controls and major depressive disorder (MDD) as done before (Heininga et al., 2019; van Loo et al., 2023). This comes from recent findings by Liu et al. (2024), who demonstrated that PA and NA reactivity to subjectively-rated positive events was highest in the sub-threshold depression group, instead of the MDD group, suggesting the possibility of a non-linear relationship between reactivity and depression severity. This runs contrary to the MB effect and suggests that greater affective flattening, that accompanies depression in adolescents (Watson et al., 2020), may result in blunted affective reactivity in MDD. Blunted emotional responses to positive and negative stimuli in depressed participants have been shown in lab studies (Bylsma, 2021; Rottenberg, 2017), so this may also be observed in EMA studies. Including a sub-threshold group, between controls and depressed, will help assess this interesting phenomenon in future studies.

5.3. Paper 3: The Exploration-Exploitation Trade-Off

5.3.1. Methodology & Findings

Paper 3 adopted several novel approaches, taking cues from prior research to make improvements. This study adapted the probabilistic reward and effort learning task from Skvortsova et al. (2014). The task required participants to learn to minimize effort or maximize reward, and subjectively rate their “liking”, “wanting” and “willingness to exert effort” (or motivation) for the rewards.

The task captured many of the stages of the TEP cycle (Figure 1). The structure of each trial, as portrayed in Figure 1 of Paper 3, demonstrating that participants would select one of two shapes, leading to a combination of effort and reward (high or low) where participants would exert effort by button presses to attain the reward. Learning to maximize reward and learning to minimize effort was divided into two blocks, separated by a 30-second break. For the reward learning block, participants would learn to select the shape that led to the high reward while the effort remained fixed, whereas learning to select the shape that led to the low effort in the effort learning block. The rewards used in this task were pictures of dog and puppy images, as low and high rewards, respectively. This study also measured effort exertion as the difference between actual effort exerted (button presses per second) for high and low rewards, indicating how much effort individuals exerted for high rewards compared to low rewards.

This study examined if learning is impaired at higher depression and anhedonia symptoms, and used computational modelling of choice behaviour to identify which aspects of learning could be impaired. The correlation of subjective ratings, effort exertion, reward and effort learning accuracies, and computational parameters, with anhedonia symptoms were determined while controlling for depression symptoms. This revealed their isolated relationship with the anhedonia symptom in young people, measured using widely used questionnaires, the Temporal Experience of Pleasure scale (TEPS) and the Snaith-Hamilton Pleasure Scale (SHAPS). This is a continuation of the analysis used for the previous version of this task (Frey et al., 2023), allowing for direct comparisons with prior research.

The general findings of Paper 3 included lower liking and wanting of puppy images at higher anticipatory anhedonia symptoms, while lower liking was specifically associated with higher consummatory anhedonia symptoms. These findings were expected, as deficits in pleasure experiences in anhedonia are well-established, but they also confirm the results from Frey et al. (2023). The specific association between consummatory anhedonia and lower liking, but not wanting, shows that these reward sub-processes are subjectively dissociable, which reflects their underlying neurobiological differences (Treadway & Zald, 2011). Additionally, lower willingness to exert effort was also associated with anticipatory anhedonia, confirming repeated findings across literature of motivation-related deficits in anhedonia (Horne et al., 2021). Further, Paper 3 reported that the difference in actual effort *decreased* with increasing anticipatory anhedonia, suggesting that effort for high rewards was similar for low reward in those with higher anticipatory anhedonia. This indicates that effort exertion is not modulated as a function of rewards at higher anticipatory anhedonia symptoms. Though this has been repeatedly demonstrated in schizophrenia, where patients exerted greater effort for low rewards than they did for high rewards compared to controls (Fervaha et al., 2013; Ince Guliyev et al., 2022; McCarthy et al., 2016; McCarthy et al., 2015), it is a novel finding in depression.

It is, however, the critical findings of Paper 3 that could contribute to the development of interventions pertaining to learning impairments. This paper confirmed previous findings that poorer reward learning (the shape that lead to the high reward was chosen less frequently) was associated with higher depression and consummatory anhedonia symptoms (Frey et al., 2023). This is likely due to the the blunted reward response biases in depression (Esfand et al., 2024; Pechtel et al., 2013; Pizzagalli et al., 2008; Pizzagalli et al., 2005; Vrieze et al., 2013) and anhedonia (Huys et al., 2013; Kangas et al., 2022; Liu et al., 2016; Vrieze et al., 2013). The novel finding was poorer effort learning (the shape that lead to low effort was chosen less frequently) at higher consummatory anhedonia. These findings did not survive correction for multiple comparisons.

Computational modelling helped elucidate variables that contribute to learning that may be impaired. Interestingly, for both reward and effort learning, Paper 3 was the first to report that higher temperature values correlate with increasing consummatory anhedonia. The temperature parameter (τ) pertains to the exploration-exploitation trade-off, where a higher value indicates an over-exploration of the less rewarding choices (or an under-exploitation of reinforcement history that shows which shape is the better choice), resulting in an individual less frequently selecting the better shape in the learning task. This bias in the explore/exploit behaviour could underpin the findings of poorer reward and effort learning at higher consummatory anhedonia symptoms in Paper 3. These confirm previous findings from meta-analyses, showing that individuals with higher anhedonia symptoms fail to develop a bias for the more rewarded choice in probabilistic tasks, computationally modelled to be driven by increased temperature values (Huys et al., 2013). However, mixed relationships between temperature and depression symptoms have been reported in literature reviews (Jami et al., 2025; Lloyd et al., 2024; Robinson & Chase, 2017), which together suggests that no conclusions can be reached yet on the direction of biases in temperature values in reward learning.

Further, the finding of increased temperature at higher consummatory anhedonia for effort learning is a novel finding whose underlying mechanisms are unclear. It is likely that lower willingness to exert physical effort in anhedonia (Horne et al., 2021) and fatigue potentially being a part of the experience of anhedonia (Billones et al., 2020) may contribute to anhedonic individuals finding both effort outcomes to be equally unattractive. Consequently, they would have made more variable choices, switching continuously between the two shapes. Therefore, this thesis proposes that both effort levels (35 presses for low and 60 for high) were considered to be unattractive outcomes, explaining the biases towards exploration (higher temperature) at higher consummatory anhedonia. This, however, is a speculative and needs to be further examined, which will be discussed below.

However, as these findings did not survive correction for multuple comparisons, future research will be required to further investigate how learning is impaired. Future studies will have to address limitations in this study.

5.3.2. Strengths

As far as is known, this was the first study to apply computational modelling to the data from a reward and effort learning task which captured many of the stages of the TEP cycle (Figure 1). Punishment learning, that has been modelled by Vinckier et al. (2022), can be argued to be similar to effort learning, in that both require individuals to learn to *avoid*. However, while punishment is an outcome, effort precedes a rewarding outcome. Further, greater effort is shown to enhance how rewarding an outcome is perceived to be (Inzlicht et al., 2018). This further distinguishes effort from punishment, because though the desirability of high effort may be flexible, punishment will always remain an undesirable outcome. Therefore, explicitly examining effort learning and how the computation of effort is impaired with increasing anhedonia symptoms is necessary. This study was also the first to do so, as far as is known.

This task was adapted to divide reward and effort learning trials into separate blocks. This was an improvement on previous versions of the task as identified by Frey et al. (2023), who showed that learning to maximize reward was significantly better than learning to minimize effort in their sample, in an interleaved trial design. Paper 3 reported, using within-subject comparisons, that effort and reward learning did not differ significantly, suggesting that the block structure removed the competition between effort and reward learning that was seen in a task with interleaved trials. This task should be repeated in future studies.

The strength of using primary rewards (puppy/dog images) was that they could be administered in an online version of the task, that allowed for a larger sample to be recruited than a lab-based task. It also allowed Paper 3 to examine learning about rewards like pleasant images that have innate value for human beings (Sescousse et al., 2013), rather than the often-used secondary rewards like money. Further, as baby animals are often rated to be more pleasant than adult animals (Lehmann et al., 2013), the puppy and dog images provided clear differences in likeability such that Paper 3 could confidently categorise them as high and low rewards, respectively.

This thesis notes that personal preferences were not catered for, as some people may have liked images other than puppies/dogs. Future studies could use other primary reward images such as kittens or humans babies.

5.3.3. Limitations & Future Directions

An important limitation in interpreting the findings of this study is that many results did not survive correction for multiple comparisons, especially the relationship between temperature parameter and anhedonia symptoms. To validate this relationship, this study needs to be replicated in larger samples that captures a range of anhedonia and depression symptoms. Further, the sample in this study was mostly female and highly educated, so its findings cannot be generalised to all young people. Targeted recruitment of males will control for this confound and potentially allow the investigation of gender-based differences.

The finding of greater exploration with increasing anhedonia for effort learning was a novel finding. It was speculated above that both high and low effort levels in the task were unattractive, perhaps explaining why individuals with higher anhedonia made more variable choices (represented by increased temperature values). Incorporating larger differences between high and low effort levels could make the low effort options more attractive in future studies, which would address this speculation. Further, asking participants to rate the difficulty of completing each effort level would help directly examine if those with higher anhedonia levels rate high and low effort to be similarly difficult, which would imply that neither is a more attractive choice.

A review of experimental tasks in the introduction of this thesis identified that primary rewards could be used more in examining learning, as opposed to the frequent use of secondary rewards like money. Paper 3 complied with this, along with Frey et al. (2023), by using pleasant images of puppies contrasted with the less pleasant images of dogs. Adolescents and young adults are shown to be hypersensitive to social rewards (Altikulaç et al., 2019; Flores et al., 2018; Foulkes & Blakemore, 2016), and value it more than monetary rewards (Wang et al., 2017). Together with the findings that frequent social interactions are known to protect against depression symptoms (Campbell et al., 2022; Panaite et al., 2021; Pemberton & Tyszkiewicz, 2016), research suggests that identifying anhedonia-related impairments in learning that impede maximizing social rewards would reveal valuable treatment targets. Therefore, future versions of the task could incorporate social rewards such as smiling faces, contrasting them with less rewarding alternatives like faces with neutral expressions (Sailer et al., 2024).

Regarding potential interventions, Huys et al. (2013) provide an interesting insight, that lower reward sensitivity (a parameter that modulates the intrinsic representation of actual reward) may masquerade as higher temperature values representing over-exploration. This appears to be conceptually sound, as an intervention that improves the internal representation of rewards must then be expressed in decision-making behaviour as a reduced exploration of less rewarding choices (or an increased exploitation of reinforcement history), thereby improving the ability to maximize rewards. Positive affect treatment (PAT) is just such an intervention that engages all sub-components of reward processing: by planning enjoyable activities and imaging their outcomes (reward anticipation), savouring the pleasure from enjoyable activities (consummatory pleasure), and reinforcing the association between self-directed action and positive emotions (reward learning) (Craske et al., 2024). This appears to be an effective treatment as it has been shown to improve reward sensitivity in both depressed and control individuals (Craske et al., 2023; Craske et al., 2016) and is also associated with improved depression symptoms, whose effects appear to persist for 6 months after treatment (Craske et al., 2019). However, as identified by Lloyd et al. (2024), it has not yet been examined how PAT addresses the explore/exploit biases in depression. Therefore, future studies could examine these relationships.

5.4. Summary & Conclusions

The aim of this thesis was to examine reward processing in young people with depression and anhedonia symptoms, and how it can be manipulated to increase engagement in leisure activities and social company, known to protect against depression symptoms. For this, the studies used EMA to examine reward processing in real-life, and the reward and effort learning task to assess learning.

Examining time-lagged relationships in EMA data revealed that increasing anticipatory pleasure for future events would increase engagement in leisure and social company, and also enhance enjoyment, in depressed individuals. Further, engaging in these activities was shown to both stabilise and enhance the reductions in negative emotions in those with higher depression symptoms. The reward and effort learning task revealed computational impairments at higher anhedonia symptoms, such that anhedonic individuals over-explored the less rewarding options (or under-exploited learned reinforcement history) when aiming to maximize reward or minimize effort. These findings, however, did not survive correction for multiple comparisons, so replication in larger samples will be required.

From these findings, this thesis has identified that Episodic Future Thinking (EFT) is a potential intervention. This is a cognitive exercise in prospection, where individuals imagine positive future events and describe in detail the feelings, thoughts, context and actions related to the forthcoming activities, thereby directly targeting the experience of anticipatory pleasure. This would exploit the time-lagged relationships identified in this thesis, but requires future studies to examine if EFT increases enjoyment and engagement in leisure activities and social company in depressed individuals. Further, re-orienting young people with higher depression symptoms to manage negative emotions by engaging in enjoyable activities may be more effective in elevating mood and maintaining long-term engagement.

These studies were successful in building up from previous research, making improvements where possible. Adapting the task into a block design, instead of an interleaved trial structure, prevented competition between reward and effort learning. The EMA protocol captured self-reported anticipation and motivation of planned activities, which allowed for their predictive capacities to be examined for future enjoyment and engagement. Moreover, for the first time, this study examined time-lagged relationships for the same events.

However, some general limitations need to be addressed. The samples were mostly highly educated females, thereby limiting generalizability. Further, the methodologies adopted in the papers were novel, so replication of these studies is essential to validate findings. Lastly, delving deeper into social experiences in replication studies would help examine how young people process personally meaningful rewards, which are also known to protect against depression symptoms.

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6. Appendices

6.1. Ethics Approval for the EMA Study (Papers 1 & 2)

From: PCLS Ethics <pclsethics@reading.ac.uk>
Date: Tuesday, 7 November 2023 at 17:04
To: Angad Sahni <a.sahni@pgr.reading.ac.uk>, Ciara McCabe <c.mccabe@reading.ac.uk>
Subject: RE: Ethics Approval 2023-150-CM (formerly 2021-090-CM)

Dear Angad,

I am pleased to inform you that changes to this project (2023-150-CM) have been reviewed by the School Research Ethics Committee and given a favourable ethical opinion for conduct. The project may proceed.

Best wishes,
Kath

PCLS Ethics
School of Psychology and Clinical Language Sciences
pclsethics@reading.ac.uk | https://www.reading.ac.uk/academic-governance-services/research-ethics

6.2. Ethics Approval for the Task Study (Paper 3)

From: PCLS Ethics <pclsethics@reading.ac.uk>
Date: Thursday, 17 November 2022 at 09:53
To: Angad Sahni <a.sahni@pgr.reading.ac.uk>
Cc: Ciara McCabe <c.mccabe@reading.ac.uk>
Subject: RE: Ethics Amendment: 2021-120-CM.

Dear Angad,

I am pleased to inform you that changes to this project (2021-120-CM) have been reviewed by the School Research Ethics Committee and given a favourable ethical opinion for conduct. The project may proceed.

Best wishes,
Kath