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Real-Life Validation of Reduced Reward Processing in Emerging Adults With Depressive Symptoms

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Subclinical symptoms of depression are common in emerging adults. Anhedonia is one such symptom that specifically puts one at risk for developing clinical depression. Recently, important progress has been made in elucidating the underlying neurobiology of anhedonia. This progress rests on many experimental studies examining how subjects with depressive symptoms respond to anticipating and consuming rewarding stimuli. Translating these findings to real-life reward processing dynamics is an important next step in order to guide fine-tuning of preventive treatments. We propose that the Experience Sampling Methodology (ESM) represents a useful tool in addressing this issue. ESM requires individuals to carry a device that beeps at semirandom moments, inviting them to fill out a short questionnaire on mood, context, and behavior. Using this methodology, we aimed to decompose the construct of reward processing into its daily life dynamics, by investigating how positive affect (PA), reward anticipation and active behavior influence each other over time. A group of emerging adults (aged 16–25) was included, of which two-thirds presented with subclinical depressive symptoms. Associations between PA, reward anticipation and active behavior manifested in the flow of daily life. Depressive symptoms were significantly associated with reduced time-lagged associations between reward anticipation and active behavior ($\beta = -.005$, $p = .006$) and active behavior and reward anticipation ($\beta = -.002$, $p = .027$). The moderating effect of depressive symptoms on the time-lagged association between reward antici-

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pation and PA approached significance ($\beta = -.002$, $p = .051$). These findings represent an important step in translating experimental knowledge on reward processing into daily life processes.

General Scientific Summary
The current study suggests that findings from carefully controlled laboratory studies regarding the experience of positive emotions can be translated into day-to-day experiences and behaviors. This was investigated in a group of young people experiencing mild depressive symptoms. We suggest that this information can help the development of treatments that prevent the worsening of these symptoms.

Keywords: anhedonia, subclinical depression, reward processing, experience sampling methodology, emerging adults

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It is well known that the incidence of major depressive disorder (MDD) increases sharply around and after puberty (Beesdo et al., 2009) and that earlier onset of MDD is associated with more impairment (Zisook et al., 2007). Moreover, MDD diagnosis is often preceded by the presence of subthreshold or prodromal symptoms (Iacoviello, Alloy, Abramson, & Choi, 2010), that themselves have significant clinical and societal impact (Lewinsohn, Solomon, Seeley, & Zeiss, 2000; Rodríguez, Nuevo, Chaterji, & Ayuso-Mateos, 2012) and put individuals at risk for developing MDD (Klein, Shankman, Lewinsohn, & Seeley, 2009). It is therefore crucial to shift our attention to the study of young individuals with subthreshold symptoms in order to obtain more insight into the development of MDD.

Anhedonia, often defined as a loss of interest and/or pleasure, is one of the symptoms likely to be present among individuals entering a depressive episode (Iacoviello et al., 2010). The presence of anhedonia predicts the onset and poor course of MDD in adults (Spijker, Bijl, de Graaf, & Nolen, 2001; Wardenaar, Giltay, van Veen, Zitman, & Penninx, 2012), specifically when anhedonia is present during adolescence (Wilcox & Anthony, 2004). During the transition from childhood to adulthood one is facing many new contexts for which new behaviors and skills need to be acquired. Reduced pleasure and interest in generally pleasant experiences can significantly interfere with this development. The current paper therefore focuses on the dynamics of anhedonia, particularly in a young population with subclinical symptoms of depression.

Neurobiological and Experimental Approaches to Anhedonia

From neurobiological research we know that pleasure processing has its roots in the brain reward system: a widespread network of neural pathways that mediate an organism's behavior toward goals that are normally beneficial for both the individual and the species (Naranjo, Tremblay, & Busto, 2001). The brain reward system undergoes dramatic changes during and after puberty, the same time that MDD incidence rises (Paus, Keshavan, & Giedd, 2008), underlining the notion that reward processing in adolescence can be an important mechanism underlying the development of MDD (Forbes & Dahl, 2012).

Over the last two decades it has become clear that "hedonia" or pleasure does not represent a unitary construct (Berridge, Robinson, & Aldridge, 2009), and hence the term "anhedonia" required improved conceptualization. Berridge and Robinson (2003) parsed reward processing into three main components: Motivation (involving both implicit and explicit Wanting processes), Affect (implicit and explicit Liking processes, or sometimes called the hedonic impact of a stimulus) and Learning (including both cognitive and associative processes; see also Berridge et al., 2009). All components are supposed to interact continuously to guide behavior, but when teasing apart the temporal dynamics of reward processing, Wanting processing tends to dominate the appetitive phase, or when anticipating a reward, while Liking processing occurs mostly during the consummatory phase, when confronted by the reward (Thomsen, Whybrow, & Kringelbach, 2015).

As a result of this finer-grained conceptualization of hedonia Treadway and Zald (2011) made the case for distinguishing between anticipatory and consummatory anhedonia. There is indeed experimental evidence in adults that depressive symptoms are associated with deficits in motivation for, and in the ability to modulate behavior as a function of pleasurable stimuli, more so than with a loss of the pleasure experience per se when confronted with these stimuli (Thomsen et al., 2015; Whitton, Treadway, & Pizzagalli, 2015). Studies in young populations also show diminished reward seeking to be present in recently depressed boys (Forbes, Shaw, & Dahl, 2007), in youngsters with a familial risk of depression (Mannie, Williams, Browning, & Cowen, 2015; Rawal, Collishaw, Thapar, & Rice, 2013) and in individuals with pediatric depression and anxiety (Morris, Bylsma, Yaroslavsky, Kovacs, & Rottenberg, 2015).

In sum, neurobiological and experimental research has increased our understanding of anhedonia significantly, and altered experimental measures of reward processing have been linked to symptoms of depression in both adult and younger populations. However, even though experimental methods generally have high internal validity, and allow for systematic examination of causal factors, the ecological validity of these paradigms is often less well examined (Myin-Germeys et al., 2009; Trull & Ebner-Priemer, 2013; Wilhelm & Grossman, 2010). In the current study we used the Experience Sampling Method (ESM) to investigate whether reward processes can be translated in daily life emotional and behavioral experiences.

Daily-Life Network Approach to Anhedonia

In ESM, participants report their current states of affect, behavior, and daily context several times a day for multiple consecutive days (Myin-Germeys et al., 2009). Translating the abovementioned reward constructs, often termed Liking, Wanting and Learning, into daily life mechanisms is a challenging endeavor. Previous ESM literature in depressed, adult, populations mostly looked at Positive Affect (PA) reactivity to pleasant events, which can be interpreted as a Liking response. One such study reported heightened reactivity in individuals diagnosed with depression compared to healthy controls (Peeters, Nicolson, Berkhof, Delespaul, & deVries, 2003) but two other studies reported no differences between groups (Bylsma, Taylor-Clift, & Rottenberg, 2011; Thompson et al., 2012). Moreover, in adolescents no difference in overall PA level was reported in youth at high versus low familiar risk for depression (Olino et al., 2014), nor were depressive symptoms found to be associated with PA reactivity in both an early and late adolescent sample (van Roekel et al., 2016). The absence of consistent associations between depressive symptom and PA reactivity is in line with experimental literature indicating a relatively intact Liking response in depression (Thomsen et al., 2015).

Despite experimental literature indicating that MDD is associated with alterations in reward processing during the appetitive phase (Treadway & Zald, 2013), fewer studies have examined daily life Wanting processes in MDD. The abovementioned study in adolescents by van Roekel et al. (2016) characterized daily life motivation as the proportion of all reported events being positive events. It was found that adolescents with depressive symptoms indeed reported relatively fewer positive events. This characterization, however, is a rather indirect measure of Wanting processing.

Wu et al. (2016) specifically investigated the anticipatory phase of pleasure in daily life in adults with MDD. Even though the authors report that, in MDD, pleasure was blunted during anticipation of daily activities, the specific ESM question targeting this construct did not concern how much subjects enjoyed the anticipation of a certain activity, but the predicted pleasure of this activity. The most established self-report scale measuring Wanting experiences (the Temporal Experience of Pleasure Scale [TEPS; Gard, Gard, Kring, & John, 2006]) formulates anticipatory pleasure not in terms of predicted pleasure, but in terms of a conscious experience of desire. To our knowledge, no study has applied this specific concept in an ESM format.

The Current Study

With the current study we believe we can expand the abovementioned research in several ways. First, to improve insights into the dynamic course of MDD the present study included individuals aged 16 to 25, that is, an age period during which onset of MDD peaks. About two thirds of the sample presented with subthreshold depressive symptoms the rest reported very few to no symptoms. In line with the RDoC approach (Insel et al., 2010), however, the group was initially analyzed as one, thereby investigating the dimensional effect of depressive symptoms on daily life reward processing. Secondary analyses looked at differences between two subgroups of the complete sample, namely the group of participants who reported no depressive symptoms at all and the group of participants who reported at least moderate symptoms.

Second, we decided on a different approach to quantifying the Liking process as PA reactivity to active behavior, rather than reactivity to self-reported pleasantness of an event. In line with the model underlying Behavioral Activation (BA) treatment (Dimidjian, Barrera, Martell, Munoz, & Lewinsohn, 2011), active behavior provides for situations in which one can encounter relatively many rewards. This idea coincides with a temporal conceptualization of reward processing by Kring and Barch (2014) in which pleasure follows approach behavior. Active behavior in our protocol could involve anything from engaging with friends, working or being physically active.

Third, the current study is the first to examine daily life *current* anticipation to future rewards in the context of depression research. The ESM item in the present study asked subjects how much they were *currently* looking forward to future events (we will refer to this item as "Reward Anticipation"). In addition, motivation for rewards is often assessed experimentally by measuring behavior, that is, how much physical effort participants are willing to exert to obtain a reward (Treadway, Bossaller, Shelton, & Zald, 2012). Hence, we examined the time-lagged association between Reward Anticipation and active behavior in order to assess how much anticipating a reward actually lead to an increase in active behavior.

Lastly, rather than looking at the abovementioned processes in isolation, the current study integrated them in a network visualization, using a similar approach as Borsboom and Cramer (2013); Klippel et al. (2017); Wichers (2014); Wigman et al. (2015). In this approach, the time-lagged associations between all network components are visualized in one network structure in which the single associations between states are not the main focus per se. Rather, the functionality of the network as a whole is of interest. Since real-life reward processing is likely to be a dynamic process in which components continuously affect each other, we applied this network approach to the three abovementioned constructs (positive affect, reward anticipation and active behavior).

We propose that positive network loops between all three abovementioned ESM items (positive affect, reward anticipation and active behavior) are an indication of a good functioning reward system as this indicates that behavioral, motivational, and emotional reward components stimulate each other. We therefore hypothesized that the more depressive symptoms subjects report, the more they show a reduced dynamic interplay in the above-described network.

Method

Participants

Participants took part in the SMARTSCAN study, a randomized controlled trial addressing the effect of psychotherapeutic training on brain and daily life functioning conducted at Maastricht University Medical Centre (Dutch Trial Register nr.: NTR3808). The current manuscript does not concern the treatment effect and hence only baseline data were used.

Participants (aged 16–25 years) were recruited via advertising in public places as well as through social media. A small group (n = 20) of participants with depressive symptoms, who applied but who lived too far away to fully participate, was asked to only

provide ESM data in order to enhance statistical power for the current analyses.

Participants were included in the time period between September 2013−January 2017 based on the following inclusion/exclusion criteria: one group comprised of participants with (sub-) clinical symptoms of depression based on a Montgomery-Åsberg Depression Rating Scale (MADRS; Montgomery & Åsberg, 1979) score of ≥10 (see the supplemental materials for a detailed description of this clinical interview). Participants were excluded if they had current psychological or psychiatric treatment and/or a significant need for care as assessed by a psychiatrist. A second group comprised participants with a MADRS score <10 and no current and/or lifetime diagnosis on the Mini International Neuropsychiatric Interview (MINI, see supplemental materials for more information; Overbeek, Schruers, & Griez, 1999) and current and/or lifetime psychological or psychiatric treatment. Two participants developed depressive symptoms during participation in the study. Since the SMARTSCAN protocol has a mirrored design data of these two participants of the second time point were included in the current analyses and treated as baseline data.

The Medical Ethics Committee of Maastricht University Medical Centre approved all study procedures (protocol number: NL41929.068.12/METC 12–2-072), and all participants signed an informed consent form (additionally signed by their proxy if age <16).

Procedure

The focus of the current manuscript is on baseline ESM data; hence only procedures relevant to the current analyses will be discussed. Potential participants were screened by phone to check for availability during the study period along with the likelihood of meeting in- and exclusion criteria. At baseline the MINI (Overbeek et al., 1999) and MADRS (Montgomery & Åsberg, 1979) were administered by trained interviewers and participants received a one-on-one explanation of the ESM procedure. Participants then carried a dedicated device for 7–21 days (see below for details).

ESM

ESM is a momentary assessment method to examine participants in their daily life environments, thus providing repeated in-the-moment measures of affect, context and behavior in a prospective and ecologically valid manner with several advantages over retrospective questionnaires (Csikszentmihalyi & Larson, 1987). An ESM protocol very similar to ours has previously been applied in an adolescent (Pavlickova, Turnbull, Myin-Germeys, & Bentall, 2015) as well as a young adult (Barrantes-Vidal, Chun, Myin-Germeys, & Kwapil, 2013) sample in collaboration with our research group. Additionally, similar ESM protocols have been applied in similar age ranges by other research groups (van Roekel et al., 2016).

In the current study, participants received a dedicated device (the PsyMate), which was programmed to emit a signal (beep) at unpredictable moments, but certainly once every 90 mins between 07:30 and 22:30 (i.e., 10 beeps a day). At each beep, participants completed a brief beep-questionnaire in the PsyMate including reports on current mood, context and activities, all given on a 7-point Likert scale. Participants were able to fill in the questionnaire up to 10 min after the initial beep but were asked to fill in the questionnaires as soon as possible in order to reduce recall bias. Most of the participants carried the device with them for 15 days (receiving 150 beeps), the subgroup of 20 participants who only provided ESM data, did so for 21 days (receiving 210 beeps), and two participants, that were initially included in another arm of SMARTSCAN but fulfilled criteria for the current sample, did so for 7 days (receiving 70 beeps). Following earlier work, participants who filled in less than 30% of received beeps were excluded from analyses (Delespaul, 1995).

Measures

Positive affect (PA). PA was measured by averaging several mood adjectives assessed at each beep. Adjectives were selected based on previous experience of our research group within this field (e.g., Myin-Germeys, van Os, Schwartz, Stone, & Delespaul, 2001; Wichers et al., 2012) in combination with the following considerations: they should reflect state (rather than trait) measures and should show sufficient intraindividual variation. Items should, furthermore, load on the same latent factor (PA), as assessed by principal component analysis with oblique rotation (on within-person mean-centered variables). The mood adjectives "cheerful," "relaxed," "satisfied," "enthusiastic," and "energetic" all loaded on the PA factor. PA was then computed by averaging the above items per participant and beep moment.

Reward anticipation. This construct was measured at each beep with the following items; first participants were asked to think about the most important situation they thought would occur the next hour and then to rate how much they were looking forward to this situation. To gain some insight into what sort of events people were looking forward to, participants were also asked to categorize this most important event into "Work/School," "Household," "Physical exercise," "Active relaxation," "Passive relaxation," "Nothing," or "Eating/Drinking."

Active behavior. Active behavior was assessed with the item "I am actively engaged in something". Participants were additionally asked to categorize what they were doing into "Work/School," "Household," "Taking care of self," "Taking care of other," "Doing sports," "Active relaxation," "Passive relaxation," "Social contact," "Online social contact," or "Eating/drinking."

Statistical Analyses

ESM data have a hierarchical structure. Thus, multiple observations (Level 1) are clustered within participants (Level 2). Multilevel (mixed effects) linear regression analyses take the variability associated with each level of nesting into account (Snijders & Bosker, 1999). The XTMIXED command in STATA 13.1 (StataCorp, 2013) was used to perform these analyses. The analysis plan involved three steps:

1. It was investigated whether a network structure between the three reward-related concepts (PA, reward anticipation and active behavior) could be identified within the complete sample. For this, three regression models were fitted in which each of the three-above mentioned ESM constructs once served as the outcome variable. The time-lagged (t-1) version of all 3 variables served as predictors in each model

(Bringmann et al., 2013) by using the combination of tsset and the time-series operator "L." in STATA 13.1 (StataCorp, 2013), not allowing the first beep of a day to be predicted by the last beep of the previous day. Analyses were controlled for two potential confounding factors: a time variable (in minutes from the first completed questionnaire) to account for any time trends in the outcome variables and age (in years). Al three models included a random intercept and slopes were treated as random effects. Covariance structure was set to unstructured.

2. To examine whether the association between the reward-related predictors and outcome variables of the models depended on MADRS score, the predictors of the above-described model were interacted with total MADRS score (in line with our hypotheses one sided p-values are reported).

3. The models described in step 2 were repeated, only this time entering a group-variable in the interaction rather than the total MADRS-score to examine group-differences in associations between predictors and outcomes. These analyses were performed in two subgroups; one including participants with a MADRS-score of 0 (healthy controls, or HC, $n = 20$) and one including participants with a MADRS-score of at least 20 (Depressive Symptoms, or DS, $n = 22$) indicating a moderate depression severity as determined by Snaith, Harrop, Newby, and Teale (1986). Since not all the complete models (including random intercepts and slopes and unstructured variance-covariance matrix) converged in this smaller sample a permutation procedure was applied in order to obtain p values of the effects (see supplemental materials for a detailed description of this procedure).

Results

Participants

Based on the in- and exclusion criteria, a total of 153 participants (age in years: $M = 20.7$, $SD = 2.2$, range = 16–25; 81% female) were included. A total of 17 participants dropped out after the first meeting and hence were not included in the current analyses. Additionally, three subjects were excluded based on not completing at least 30% of valid beep questionnaires. Table 1 displays sociodemographic and clinical characteristics of the final sample ($n = 133$).

The two subgroups consisted of $n = 20$ HC subjects and $n = 22$ DS subjects. Table 2 displays the sociodemographic and clinical characteristics of these two groups. The groups did not differ significantly with regard to age, gender, employment status, and/or current/highest education (all p values >0.05).

Associations Between Reward Network Items and Total MADRS Score

Total MADRS score was significantly negatively associated with average PA ($\beta = -.058$, $p < .001$) and reward anticipation ($\beta = -.033$, $p < .001$) but not with active behavior ($\beta = -.005$, $p = .674$).

Table 1
Summary of Demographic and Clinical Characteristics and of ESM Reward Network Items and Percentage of Beeps Subjects Reported Looking Forward to, or Being Actively Engaged in, a Certain Activity

Variable	$n = 133$
Demographic characteristics	
Age (*M*, *SD*, range)	20.7 (2.2) 16–25
% female	80% ($n = 107$)
Employment status	
At school/studying	89% ($n = 118$)
Part-time/fulltime work	9% ($n = 12$)
Voluntary work	1% ($n = 1$)
Current/highest education	
Secondary school	11% ($n = 14$)
IVE	3% ($n = 4$)
BSc	69% ($n = 91$)
MSc	18% ($n = 24$)
Clinical characteristics	
MADRS score (*M*, *SD*, range)	11.4 (8.0) 10–27
History of AD use	5% ($n = 6$)
History of individual psychotherapy	30% ($n = 40$)
ESM items	
Positive Affect (*M*, *SD*)	4.33 (BS: .79, WS: .95)
Reward Anticipation (*M*, *SD*)	4.90 (BS: .75, WS: 1.49)
Work/school[a]	31%
Household	4%
Physical exercisea	3%
Active relaxationa	10%
Passive relaxationa	17%
Nothinga	2%
Eating/drinkinga	11%
Active Behavior (*M*, *SD*)	3.22 (BS: .99, WS: 1.59)
Work/school[b]	26%
Household[b]	6%
Taking care of self[b]	5%
Taking care of others[b]	1%
Doing sports[b]	1%
Active relaxation[b]	6%
Passive relaxation[b]	20%
Social contact[b]	10%
Online social contact[b]	3%
Eating/drinking[b]	8%

Note. *SD* = standard deviation; IVE = intermediate vocational education; BSc = Bachelor level education; MSc = Master level education; MADRS = Montgomery-Åsberg Depression Scale; AD = antidepressant medication; ESM = Experience-Sampling Methodology; BS = between subject standard deviation; WS = within subject standard deviation.
[a] After subjects indicated how much they were looking forward to what was going to happen the next hour they categorized the type of this event in one of these categories. [b] After subjects indicated how actively they were engaged in what they were doing they categorized the activity in one of these categories.

ESM Reward Network and Continuous MADRS Score

Within the entire sample ($n = 133$), significant time-lagged associations could be found between all reward concepts except for the mutual associations between reward anticipations and active behavior (see Figure 1a, the numbers with the arrows indicate regression coefficients). However, total MADRS score specifically moderated these two associations; the higher the MADRS score, the smaller the time-lagged mutual associations between reward anticipation and active behavior.

Additionally, the interaction effect between reward anticipation and total MADRS score on PA approached significance, indicating

Table 2
Summary of Demographic and Clinical Characteristics and of ESM Reward Network Items and Percentage of Beeps Subjects Reported Looking Forward to, or Being Actively Engaged in, a Certain activity, Separately for Each of the Two Sub-Groups

Variable	DS (n = 22)	HC (n = 20)
Demographic characteristics		
Age (*M*, *SD*, range)	20.5 (2.7) 16–25	21.3 (1.9) 18–25
% female	95% (n = 21)	70% (n = 14)
Employment status		
At school/studying	77% (n = 17)	90% (n = 18)
Part-time/full-time work	18% (n = 4)	10% (n = 2)
Voluntary work	5% (n = 1)	
Current/highest education		
Secondary school	14% (n = 3)	
IVE		5% (n = 1)
BSc	73% (n = 16)	60% (n = 12)
MSc	14% (n = 3)	35% (n = 7)
Clinical characteristics		
MADRS score (*M*, *SD*, range)	22.1 (2.2) 20–27	
History of AD use	5% (n = 1)	
History of individual psychotherapy	50% (n = 11)	
Positive Affect (*M*, *SD*)	3.80 (BS:.64, WS:1.01)	5.10 (BS:.82, WS:.83)
Reward Anticipation (*M*, *SD*)	4.63 (BS:.82, WS:1.66)	5.44 (BS:.80, WS:1.25)
Work/school[a]	38%	32%
Household[a]	4%	4%
Physical exercise[a]	2%	3%
Active relaxation[a]	10%	10%
Passive relaxation[a]	14%	17%
Nothing[a]	3%	1%
Eating/drinking[a]	7%	13%
Active Behavior (*M*, *SD*)	3.40 (BS:1.11, WS:1.58)	3.46 (BS:.94, WS:1.64)
Work/school[b]	29%	28%
Household[b]	6%	7%
Taking care of self[b]	6%	4%
Taking care of others[b]	1%	1%
Doing sports[b]	1%	2%
Active relaxation[b]	6%	5%
Passive relaxation[b]	18%	20%
Social contact[b]	8%	8%
Online social contact[b]	4%	2%
Eating/drinking[b]	6%	9%

Note. DS = depressive symptoms (MADRS ≥ 10); HC = healthy controls (MADRS = 0); *SD* = standard deviation; IVE = intermediate vocational education; BSc = Bachelor level education; MSc = Master level education; MADRS = Montgomery-Åsberg Depression Scale; AD = antidepressant medication; ESM = Experience-Sampling Methodology; BS = between subject standard deviation; WS = within subject standard deviation.
[a] After subjects indicated how much they were looking forward to what was going to happen the next hour they categorized the type of this event in one of these categories. [b] After subjects indicated how actively they were engaged in what they were doing they categorized the activity in one of these categories.

that it is plausible that the higher the MADRS score, the less likely that increases in reward anticipation are to be followed by increases in PA. Associations that were moderated by total MADRS score are indicated by a lightning symbol in Figure 1a, symbolizing the disruption in the associations. Table 3 displays the corresponding p value of each coefficient in Figure 1a; Table 4 displays the coefficients and p values for the interaction effects.

ESM Reward Network per Subgroup

Figure 1b displays the ESM reward network visualizations within both subgroups. Significant coefficients are indicated with an asterisk. Table 5 displays the corresponding p value of each coefficient.

HC group. Descriptively, this group showed the following significant time-lagged associations: PA and reward anticipation positively reinforced each other; the more participants were looking forward to what was going to happen, the more they experienced positive emotions the next moment and the more they experienced positive emotions the more their reward anticipation increased one moment later. Reward anticipation positively predicted active behavior; the more participants were looking forward to what was going to happen in the near future, the more they showed active behavior one moment later.

DS group. Descriptively, this group showed the following significant time-lagged associations: similar to the HC group, positive associations between PA and reward anticipation. In addition, they

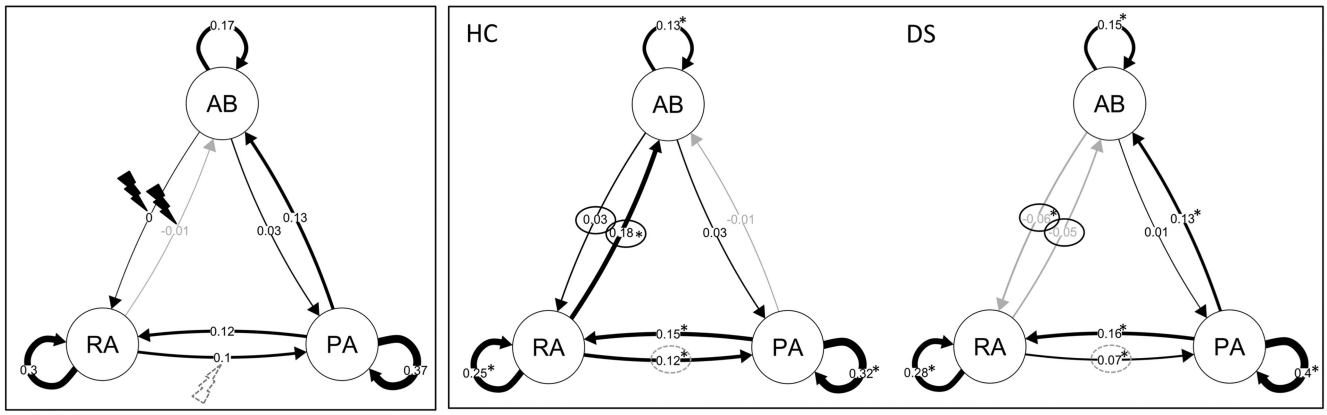

Figure 1. Graphic display of connections within ESM reward networks, generated using the qgraph-package (Epskamp, Cramer, Waldorp, Schmittmann, & Borsboom, 2012). Arrows represent the strength of the connections between any two pairs of items (one emotion at time t – 1 and the other at time t). Black edges correspond to positive connections, gray edges correspond to negative connections. Thick edges represent stronger connections; the thinner the edge, the weaker the connection. Numbers with the edges represent β-coefficients. (a) Network visualization in the complete sample (n = 133). Lightning symbols indicate the associations in the network that are moderated by total MADRS score (black: $p < .05$, gray: $p < .10$). (b) Network visualization within the two subgroups. Significant coefficients within a group are indicated with an asterisk, significant differences between coefficients of the two subgroups are indicated by circled coefficients (black: $p < .05$; gray and dashed: $p < .10$). DS = group of subjects with subclinical depressive symptoms (MADRS ≥ 20); HC = control group (MADRS = 0); PA = Positive affect, RA = reward anticipation; AB = active behavior.

showed a positive association between PA and active behavior. Interestingly, the negative effect of reward anticipation on active behavior approached significance and the negative effect of active behavior on reward anticipation was significant. Hence, in the DS group, reward anticipation and active behavior negatively reinforced each other.

ESM Reward Network Differences Between the Two Subgroups

Significant group differences in network coefficients are marked by a circle in Figure 1. The groups differed significantly with regard to the association between reward anticipation and active behavior, active behavior and reward anticipation (for both effects: HC group positive association, DS group negative association), and the difference in the effect of reward anticipation on PA approached significance (HC group stronger association than DS group).

Table 3
Effect Sizes (β-Coefficient) and p-Values of Time-Lagged Associations Between ESM Reward Network Items in the Complete Sample, Controlled for Time (in Minutes) and Age (in Years)

Outcome (time t)	Predictor (time t–1)	Beta (*SE*)	*p*-value
Positive affect	PA	.366 (.018)	<.001
	RA	.103 (.009)	<.001
	AB	.029 (.006)	<.001
Reward anticipations	PA	.119 (.0229)	<.001
	RA	.301 (.017)	<.001
	AB	.001 (.010)	.479
Active behavior	PA	−.012 (.016)	<.001
	RA	.126 (.026)	<.001
	AB	.172 (.014)	.464

Note. *SE* = Standard Error; MADRS = Montgomery-Åsberg Depression Scale; PA = positive affect; RA = reward anticipation; AB = active behavior.

Discussion

The current paper aimed at translating experimental findings on reward processing into daily life mechanisms in emerging adults with subclinical depressive symptoms. We took constructs from the experimental and neurobiological literature and were able to show that time-lagged associations between these constructs exist in daily life. This in itself is a major contribution to the field since it shows that that it is possible to map out how these constructs dynamically influence each other in a person's natural environment.

More specifically, analyses in the complete sample revealed a pattern in which reward anticipation resulted in more PA some time later, which in turn predicted more active behavior. The reverse pattern was also found, in that more active behavior resulted in more PA, leading in turn to more reward anticipation. These dynamics illustrate the complex interplay between different reward components, as described in experimental literature (Berridge et al., 2009; Kring & Barch, 2014), in daily life. Interestingly, the two associations (between reward anticipation and active behavior) that were not found to be significant in the complete sample were the ones that were moderated by total MADRS score, thereby showing that increased depression severity is mainly associated with disturbances in how reward anticipation and active behavior influence each other.

Table 4
Effect Sizes (β-Coefficient) and p-Values of the Interaction Effect Between Total MADRS Score and Time-Lagged Associations Between ESM Reward Network Items in the Complete Sample, Controlled for Time (in Minutes) and Age (in Years)

Outcome (time t)	Predictor (time t–1)	Beta (*SE*)	*p*-value
Positive affect	PA × MADRS	.002 (.002)	.853
	RA × MADRS	−.002 (.001)	.051
	AB × MADRS	−.001 (.001)	.205
Reward anticipations	PA × MADRS	.001 (.003)	.662
	RA × MADRS	−.002 (.002)	.173
	AB × MADRS	−.002 (.001)	.027
Active behavior	PA × MADRS	<.001 (.003)	.523
	RA × MADRS	−.005 (.002)	.006
	AB × MADRS	<.001 (.002)	.595

Note. *SE* = Standard Error; MADRS = Montgomery-Åsberg Depression Scale; PA = positive affect; RA = reward anticipation; AB = active behavior.

Temporal Dynamics of Reward Processing in the Lab Versus Daily Life

In the set-up of the three reward constructs in our network we assumed that the PA reactivity to active behavior is an indication of Liking processing. The fact that total MADRS-score was not associated with active behavior could indicate that everyone might have been confronted with an equal amount of rewards. More importantly, the associations between active behavior and PA was not moderated by MADRS score (and also did not differ significantly between the two subgroups), indicating that the hedonic response to rewards encountered while being actively engaged did not differ between people at the low and intermediate level of the depression continuum. This finding is in keeping with, and therefore ecologically validates, the experimental literature in adults, reporting that liking, or hedonic impact of rewards, is not altered in people with depression (Clepce, Gossler, Reich, Kornhuber, & Thuerauf, 2010; Dichter, Smoski, Kampov-Polevoy, Gallop, & Garbutt, 2010; Sherdell, Waugh, & Gotlib, 2012; Ubl et al., 2015).

MADRS score was negatively associated with reward anticipation, which is in line with recent work reporting decreased striatal response during anticipation of reward in adults with clinical (Stoy et al., 2012) and adolescents with clinical (Olino et al., 2011) and subclinical symptoms of depression (Stringaris et al., 2015). In addition, MADRS score modulated the association between reward anticipation and active behavior, an effect that was mirrored

Table 5
Effect Sizes (β-Coefficient) and p-Values of Time-Lagged Associations Between ESM Reward Network Items Per Sub-Group and for the Difference Between Sub-Groups, Controlled for Time (in Minutes) and Age (in Years)

HC			
	Predictor (time t−1)		
Outcome (time t)	PA_{t-1}	RA_{t-1}	AB_{t-1}
$Positive\ affect_t$	.317 (<.001)	.124 (<.001)	.029 (.062)
$Reward\ anticipation_t$	.149 (.004)	.249 (<.001)	.032 (.176)
$Active\ behavior_t$	−.015 (.831)	.176 (<.001)	.126 (<.001)
DS			
	Predictor (time t−1)		
Outcome (time t)	PA_{t-1}	RA_{t-1}	AB_{t-1}
$Positive\ affect_t$	.401 (<.001)	.068 (<.001)	.011 (.496)
$Reward\ anticipation_t$	.158 (<.001)	.283 (<.001)	−.061 (.021)
$Active\ behavior_t$	.125 (.005)	−.050 (.073)	.150 (<.001)
DS−HC			
	Predictor (time t−1)		
Outcome (time t)	PA_{t-1}	RA_{t-1}	AB_{t-1}
$Positive\ affect_t$	.084 (.895)	−.056 (.057)	−.019 (.193)
$Reward\ anticipation_t$	.009 (.529)	.034 (.639)	−.093 (.004)
$Active\ behavior_t$	.140 (.931)	−.023 (<.001)	.025 (.724)

Note. ESM = Experience-Sampling Methodology; DS = group of subjects with subclinical depressive symptoms; HC = control group; PA = Positive affect; RA = reward anticipation; AB = active behavior.

in the subgroup comparison: whenever the DS group reported increased reward anticipation, their active behavior actually tended to decrease some time later. This could mean two things; either they were more looking forward to passive activities/situations, or they were not able to translate their reward anticipation into behaviors necessary to pursue the anticipated reward. Post hoc analyses looking into group differences of reported categories of events that were going to happen in the near future (see Table 2) indicated that the DS group reported significantly less often that they were looking forward to physical exercise and eating/drinking. However, anticipation of physical exercise was only reported around 3% of the beeps. Based upon this finding, it is likely that the above-mentioned group difference indicates that DS participants were less able to modify their behavior, or felt less motivated to change their behavior, as a function of reward anticipation. Awaiting replication in a larger sample, this result is in line with experimental literature on deficits in motivation for, and behavior modulation in response to rewards (Pizzagalli, 2014; Treadway & Zald, 2011; Whitton et al., 2015).

Three Reward Processing Components in One ESM Network

Applying a dynamic network approach to psychopathology symptoms or affective states is relatively new. A number of studies have recently shown that dynamic associations between momentary affective states can be visualized in a network, thereby clarifying how the "activation" of one state can "activate" one or several other states over time (Bringmann et al., 2013; Klippel et al., 2017; Pe et al., 2015; Wigman et al., 2015). In this approach, the single associations between states are not the main focus per se, rather the functionality of the network as a whole is of interest. For example, when looking at negative affective states, it has consistently been found that participants with psychopathological complaints show stronger connections in these networks, resulting in negative states 'activating' more negative states and this negative 'activity' is thereby assumed to resonate more and longer within this network.

In the ESM reward network that was investigated in the current paper it was hypothesized that stronger connections were indicative of a healthier state, since positive loops between active behavior, positive emotions and reward anticipation imply that participants can enjoy what they are doing, can translate this affective response into reward anticipation and additionally can motivate themselves to change their behavior as a function of this anticipation. It would also imply that this network can be 'activated' from any of the three nodes, that is, by being active, by experiencing positive emotions, or by anticipating enjoyment, one enters a dynamic process that is continuously reinforced and ultimately could lead to increased approach behavior.

Increases in approach behavior is of particular relevance in the age range of focus in the current paper, since late adolescence to early adulthood is a phase in life when one has to actively approach many situations in order to acquire the skills necessary for independence (Telzer, 2016). Our hypothesis was partly confirmed in the current sample, in which it was shown that the mutual associations between reward anticipation and active behavior were reduced in participants with depressive symptoms. These findings are interesting in and of themselves, as discussed in previous paragraphs, however, within a network approach one could view these altered associations to be indicative of "weak spots" in the network, where the dynamic process of activation within the network is blocked by a disconnection between some of the nodes of the network. Less optimal reward processing, specifically when leading to reduced approach behavior, can be a mechanism by which young individuals become less active, for example, socially, physically or academically, all of which have been associated with depressive symptoms in adolescents (Field, Miguel, & Sanders, 2001; Motl, Birnbaum, Kubik, & Dishman, 2004; Pelkonen, Marttunen, & Aro, 2003).

Clinical Implications and Future Directions

Besides adding ecological validity to experimental findings, these results highlight potential targets for prevention treatments. One meta-analysis on effectiveness of prevention treatments of MDD acknowledges the importance of studying these interventions in young populations with subclinical symptoms (Muñoz, Cuijpers, Smit, Barrera, & Leykin, 2010). Although, based on this meta-analysis, it seems that effective prevention treatments exist for this population, the range of incidence of MDD in the experimental conditions still overlapped with those in the control conditions, indicating considerable heterogeneity in effectiveness as well as substantial room for improvement. So far, little is known about treatment mechanisms of these interventions, hence little information is available to direct any advancement of available treatments.

The current findings can provide guidance in the refinement of, for example, the Behavioral Activation (BA) component that is present in many of the existing prevention treatment packages. BA generally seeks to increase the patient's contact with sources of reward; hence the reduced coupling of RA and active behavior can be a potential specific target. This can be done, for example, by not only focusing on behavior and its consequences on mood but also by pointing out how reward anticipation is supposed to motivate a person to approach whatever is anticipated. So, if one learns to recognize a pattern in which the experience of looking forward to something does not lead to approach behavior, one can put specific effort into trying to connect these constructs again. Of course, in one specific situation many things can interrupt the process between reward anticipation and action. For instance, one might need to work longer than expected, one might receive a phone call, or the traffic is bad. However, the effects we report are general tendencies, that is, examining whether, over all situations, increased reward anticipation leads to increased activity (increased approach), and the more people reported depressive symptoms, the more this effect was found to be reduced. Future research should examine the predictive value of ESM reward-dynamics like the ones reported in this study as well as whether they can indeed be affected by preventative treatments.

Moreover, current results pave the road toward a potential next step: to understand similar dynamics within single individuals, thereby contributing to a personalized medicine approach. As discussed in Wichers et al. (2011) momentary assessment, in addition to contributing to a better understanding of fine-grained affective, cognitive and behavioral dynamics in psychopathology, can be a powerful tool to collect information on individual risk and guide treatment decisions. It can, for example, be used to find out within one person what exactly the situations, contexts and/or

behaviors are that he or she enjoys most but for which motivation or approach behavior is lacking. This person-specific momentary process can then be monitored during antidepressant treatment to quickly find out subtle changes over time that might not be consciously appraised during interview sessions. This information can serve to add depth to the clinical picture used to guide decision-making on continuation or change of treatment.

Methodological Issues

One potential issue in analyzing group differences in associations between variables, like in the networks of the current paper, is the presence of floor and ceiling effects. If, for example, the mean of one variable within one group is so low or high that its distribution within that group gets skewed, this would mean that slopes of associations of predictors with that variable are artificially flattened which could invalidly increase group difference effects. We therefore carefully inspected our data and did not find gross deviations from normality. In addition, mean levels of the ESM variables of both groups in the current paper are not close to the extremes of the 7-point Likert scale and within-participants variations of these variables are relatively similar in both groups. Therefore, in all probability, this issue does not confound our results.

Second, effect sizes in the current paper are small, but comparable to other ESM studies (e.g., Myin-Germeys et al., 2001; van Winkel et al., 2015). The relevance of these effects is captured in the notion that they reflect small, but frequent impacts of one variable on the other, which over time accumulate to be influential enough to impact on mental health, as was shown in many studies (Kramer et al., 2014; Wichers, 2014; Wichers et al., 2010). The relevance of small effects is additionally endorsed by a relatively recent approach to psychopathology, which is based on complex dynamical system theory (Hayes & Strauss, 1998; Huber, Braun, & Krieg, 1999; van de Leemput et al., 2014; Wichers, Wigman, & Myin-Germeys, 2015). This approach acknowledges the fact that mood is an example of a system that is regulated by an immensely complex array of mechanisms, including biology, previous life experiences and current contextual influences, which we certainly do not yet, or might never, completely understand. One characteristic of a dynamical system is that, depending on the state of the system, it can be unstable and fragile. As such, very small perturbations can lead to major changes within the system. In sum, small daily life effects can be highly relevant, since they can either slowly accumulate over time, or, when impacting on an unstable system, can start a process of large change (van de Leemput et al., 2014).

Third, it should be noted that, in the way our ESM protocol was set up, we are not specifically measuring whether the reported reward anticipation and active behavior in consecutive beeps concerned the exact same event and/or activity. It is our opinion that, in ESM, one should refrain from influencing the behavior of the participants as much as possible in order to have the highest ecological validity. Therefore, an item enquiring whether or not one completed the anticipated activity or whether the anticipated event occurred was not included in our protocol. The reasons for this are as follows: first, an item like this (asking about specifics in the past) requires a certain level of cognitive effort and hence influences the amount of time needed to fill in the questionnaire which, consequently, will influence appliance. Second, once participants notice that they do not pursue what they anticipate, they might either experience this as failure, which could influence their mood, or they could change their behavior. Hence, we examined more general tendencies rather than very specific activity-related processing.

Fourth, although Watson and Naragon-Gainey (2010) review literature suggesting that positive emotional dysfunction is relatively specific to mood disorders, other research suggests altered reward processing, for example, in people diagnosed with Obsessive Compulsive Disorder (Wood & Ahmari, 2015), Social Anxiety Disorder when investigating social rewards (e.g., Cremers, Veer, Spinhoven, Rombouts, & Roelofs, 2015; Richey et al., 2016; Sripada, Angstadt, Liberzon, McCabe, & Phan, 2013) and schizophrenia (Whitton et al., 2015). However, based on literature showing that anxiety and depression are highly comorbid in both the clinical as well as the preclinical stage (Brown, Campbell, Lehman, Grisham, & Mancill, 2001; Preisig, Merikangas, & Angst, 2001), that a "pure" depression without anxiety is very uncommon (Brown et al., 2001) and that the development of psychosis is preceded by depressive symptoms (Häfner et al., 2005) we thought it unwise to correct our models for these specific psychopathologies.

Lastly, the permutation procedure used in the current paper is a novel approach to investigating the significance of fixed effects of multilevel models. The reason for using this approach is that the complete multilevel models (i.e., including random effects for all coefficients in addition to not posing any limitations to the variance-covariance structure of the model) do not converge easily in smaller samples. The permutation procedure offers a good alternative and since it has fewer assumptions it might even be preferred. In fact, permutation tests provide exact inferences without having to appeal to random sampling from some vague population, as we must do under the population model of statistical inference as proposed by Neyman and Pearson (e.g., Cremers et al., 2015; Richey et al., 2016; Sripada et al., 2013).

In conclusion, the current paper is the first aiming to translate experimental findings regarding altered reward processing in the development of MDD into daily life mechanisms. We did so in a young population at risk for developing MDD. It was found that temporal associations between reward anticipation and both active behavior and PA were reduced with increasing severity of depressive symptoms. These findings contribute toward ecological validation of the experimental literature and provide specific information that can be used to fine tune existing preventative treatments.

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