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Published in:
Journal of Affective Disorders

DOI:
10.1016/j.jad.2017.12.017

Publication date:
2018

Exploring the emotional dynamics of subclinically depressed individuals with and without anhedonia: An experience sampling study

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Find this article online at: https://doi.org/10.1016/j.jad.2017.12.017

Cite this article:

Bos, F.M., Blaauw, F.J., Snippe, E., van der Krieke, L., de Jonge, P., & Wichers, M. Exploring the emotional dynamics of subclinically depressed individuals with and without anhedonia: An experience sampling study. Journal of Affective Disorders, 2017. doi:10.1016/j.jad.2017.12.017

Abstract

Background. Anhedonia has been linked to worse prognosis of depression. The present study aimed to construct personalized models to elucidate the emotional dynamics of subclinically depressed individuals with versus without symptoms of anhedonia.

Methods. Matched subclinically depressed individuals with and without symptoms of anhedonia (N = 40) of the HowNutsAreTheDutch sample completed three experience sampling methodology assessments per day for 30 days. For each individual, the impact of physical activity, stress experience, and high/low arousal PA/NA on each other was estimated through automated impulse response function analysis (IRF). These individual IRF associations were combined to compare anhedonic versus non-anhedonic individuals.

Results. Physical activity had low impact on affect in both groups. In non-anhedonic individuals, stress experience increased NA and decreased PA and physical activity more strongly. In anhedonic individuals, PA high arousal showed a diminished favorable impact on affect (increasing NA/stress experience, decreasing PA/physical activity). Finally, large heterogeneity in the personalized models of emotional dynamics were found.

Limitations. Stress experience was measured indirectly by assessing level of distress; the timeframe in between measurements was relatively long with 6h; and only information on one of the two hallmarks of anhedonia, loss of interest, was gathered.

Conclusions. Our results suggest different pathways of emotional dynamics underlie depressive symptomatology. Subclinically depressed individuals with anhedonic complaints are more strongly characterized by diminished favorable impact of PA high arousal and heightened NA reactivity, whereas subclinically depressed individuals without these anhedonic complaints seem more characterized by heightened stress reactivity. The automatically generated personalized models may offer patient-specific insights in emotional dynamics, which may show clinical relevance.

Keywords: anhedonia, experience sampling methodology, depression, physical activity, stress

Introduction

Major depressive disorder (MDD) is a highly disabling disorder characterized by considerable heterogeneity (Fried & Nesse, 2015). It has been suggested that anhedonia, one of the two core symptoms of MDD (American Psychiatric Association, 2013), constitutes a distinct endophenotype of MDD (Pizzagalli, 2014; Vrieze & Claes, 2009). Anhedonia is the inability to experience interest in or pleasure from activities usually found enjoyable and is reported by roughly one third of MDD patients (Pelizza & Ferrari, 2009). It has been linked to poorer prognosis of MDD (Moos & Cronkite, 1999; Wardenaar, Giltay, van Veen, Zitman, & Penninx, 2012), poorer treatment response (Vrieze et al., 2014; Wichers et al., 2009a; Yee et al., 2015), and increased risk of suicide (Damen et al., 2013).

Despite its debilitating influence, relatively little is known about underlying mechanisms of anhedonia. In order to bridge this gap in our knowledge, we need to find better and more direct ways to study the differences between subclinically depressed individuals with and without anhedonic symptoms. By studying individuals with subclinical levels of symptoms, mechanisms that underlie the future development of clinical symptoms and disorders may be uncovered. Indeed, the dimensional perspective on psychopathology assumes that the underlying mechanisms for subclinical and clinical levels of depression and anhedonia are at least partially shared (Krueger & Piasecki, 2002). Further, such an approach requires a translation from abstract measures of anhedonia (e.g. in the laboratory) to specific emotional responses to situations in daily life. Such knowledge potentially helps in targeting anhedonia more directly and effectively.

The hypothesis that anhedonia is a distinct MDD endophenotype (Pizzagalli, 2014) suggests that different daily life dynamics underlie depressive symptoms in individuals with anhedonic symptoms versus those without. Given that anhedonia is characterized by less enjoyment of activities, subclinically depressed individuals with anhedonic symptoms might benefit less from pleasurable behaviors, as indicated by smaller increases in positive affect (PA) and smaller reductions in negative affect (NA). Physical activity might be such a pleasurable behavior, since it is generally viewed as a behavior that increases PA and is often advised to depressed patients by clinicians (Backhouse, Ekkekakis, Biddle, Foskett, & Williams, 2007). In anhedonic individuals, we would expect that the favorable impact of physical activity on affect is diminished. Further, anhedonia has been related to higher perceived stress

(Horan, Brown, & Blanchard, 2007) and the experience of stress has been found to worsen hedonic capacity and responsiveness to positive events (Pizzagalli, 2014). We would therefore expect that the experience of stress exerts a stronger unfavorable impact on affect (i.e., in reducing PA and increasing NA) for individuals with anhedonia.

Previous research has primarily focused on group-level results, e.g. mean associations that do not necessarily represent associations of individuals (Hamaker, 2012; Molenaar, 2004). Research so far may thereby have overlooked important heterogeneity in emotional dynamics. MDD is highly heterogeneous (Fried & Nesse, 2015) and the effects of physical activity have been found to vary widely across individuals (Rosmalen, Wenting, Roest, de Jonge, & Bos, 2012; Snippe et al., 2016; Stavrakakis et al., 2015). Thus, in contrast to previous research, we will examine mechanisms of anhedonia in daily life on a case-by-case basis so as to account for and gain insight into this heterogeneity. Based on individual models, we will discern more general patterns. Such a personalized approach may also have relevance for clinical practice in understanding emotional dynamics of individual patients.

Aims of the study

The present study aimed to examine emotional dynamics in the flow of daily life in subclinically depressed individuals with versus without anhedonic symptoms. Specifically, we will study the possibly differential impact of physical activity and stress experience on positive and negative affect in subclinically depressed individuals with versus without anhedonic symptoms. Such an investigation in a general population sample can be the starting point to investigate micro-level dynamics that may underlie the future development of clinical symptoms. These dynamics can be optimally measured through the ecologically valid experience sampling method (ESM, Reis, 2012). With ESM, individuals can record their affect, stress level, and level of physical activity multiple times a day in their own environments (Myin-Germeys, 2012; Shiffman, Stone, & Hufford, 2008), to prospectively examine emotional responses to physical activity and the experience of stress. We will use an advanced extension of vector autoregressive (VAR) modelling called impulse-response function (IRF) analysis (Brandt & Williams, 2007; Lütkepohl, 2005) to compare the impact of a hypothetical increase in physical activity or stress experience on affect for both subgroups. To this end, we used automated impulse-response analysis (AIRA), a novel and sophisticated *R*-package that automates IRF analyses (Blaauw, van der Krieke, Emerencia, Aiello, & de Jonge, 2017). AIRA estimates network models for each individual, after which these models can be combined into aggregated models to compare the two groups. This approach accounts for and offers insight into individual differences in daily dynamics and depressogenic mechanisms.

Method

Participants

Participants are 629 individuals from the general Dutch population who participated in an ESM protocol of the study "HowNutsAreTheDutch?" (Dutch: HoeGekIsNL?) between May 22nd, 2014 and December 13th, 2014 (end of the first-year wave of the website; van der Krieke, Jeronimus et al., 2016; van der Krieke, Blaauw et al., 2016). In order to be included, participants had to indicate they (1) were at least 18 years of age, (2) could start with the study within five days (3) possessed a smartphone with a mobile internet connection, (4) were not engaged in shift work, (5) did not anticipate a major disruption of daily routines within the study period, (6) were aware that their results would be useless if too many assessments were missed, and (7) consented to having their anonymous data used for research purposes.

For the present paper, we selected individuals who (1) were at least mildly depressed, as indicated by a Quick Inventory for Depressive Symptomatology (QIDS-SR; Rush et al., 2003) score of 6 or higher, and (2) completed at least 67 (75%) of the diary assessments (for a flow-chart, see Supplementary Figure 1). Given that anhedonia is defined as loss of interest or pleasure, we used the QIDS-SR item on loss of interest ("I notice that I am less interested in people or activities") as a proxy for anhedonia. Although this is a single item, this item seems to be a relatively valid measure of anhedonia given its high correlates to anhedonia items of Depression and Anxiety Stress Scales (DASS, Lovibond & Lovibond, 1995). In the HowNutsAreTheDutch sample (N=8575), the QIDS-SR loss of interest item correlated 0.74 with the more general loss of interest item of the DASS (Wardenaar et al. 2017) and 0.66-0.70 with the three DASS items on anhedonia (on enjoyment, experience of positive affect, and enthusiasm). Participants who endorsed this item (scored at least '1') are henceforth referred to as 'anhedonic', participants who reported no loss of interest as 'non-anhedonic'. All anhedonic individuals were matched to non-anhedonic individuals based on their QIDS-SR score, sex, and education level, respectively. This resulted in 50 matched individuals, 25 in each group.

Measures

Depressive symptoms. Depressive symptoms at the time of study entry were assessed through the QIDS-SR, a 16-item self-report questionnaire. The QIDS-SR covers all depressive symptoms as described by the DSM and shows adequate validity and reliability (Rush et al., 2003).

Diary items. Participants completed 43 items on affect, behavior, cognitions, and activities through an electronic diary three times a day for 30 consecutive days, resulting in a maximum of 90 assessments. These assessments were completed online; links to the assessments were sent via text messages. Participants had one hour to complete an assessment after receiving the notification. In the present sample, on average 76 diary assessments (*SD* = 5.3) were completed per participant. Diary items were rated on visual analogue scales (VAS) ranging from 0 ('not at all') to 100 ('very much'). To accommodate the two dimensions of affect, valence and arousal (Watson & Tellegen, 1985), four affective variables were constructed. The mean score of the emotional items 'energetic', 'enthusiastic', and 'cheerful' was taken to reflect positive affect (PA) high-arousal. PA low-arousal was assessed by 'relaxed', 'content', and 'calm'. Likewise, negative affect (NA) high-arousal was assessed by 'anxious', 'nervous', and 'irritable', and NA low-arousal by 'gloomy', dull', and 'tired'. Participants further indicated their level of physical activity of the last six hours ('since the last measurement I was physically active', item no 41) and subjective experience of stress ('I am upset', item no 25; van der Krieke et al., 2016b).

Analyses

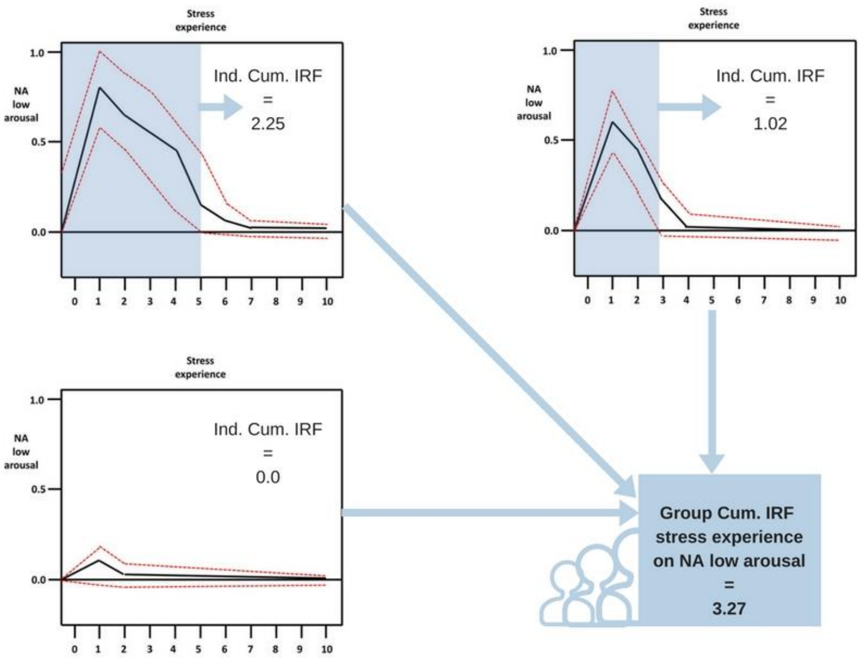
Personalized models of the dynamics between physical activity, stress experience, and affect in subclinically depressed individuals with versus without anhedonic complaints were estimated. Based on these models, we first examined our hypotheses on the potentially differential impact of activity and stress experience on the affective variables in subclinically depressed individuals with versus without anhedonic symptoms. Next, we explored other relevant differences in emotional dynamics between the two groups. Finally, we illustrated the individual differences in emotional dynamics.

First, we fitted a vector autoregression (VAR) model for every participant. In a VAR model, each variable is regressed on its own lagged values (autocorrelation) as well as the lagged values of the other variables (Brandt & Williams, 2007), resulting in a set of regression coefficients for each individual. As such, one can examine the dynamic effect of the variables on each other (e.g. the effect of physical activity at one moment in time (t) on high-arousal positive affect at the next moment in time (t+1)). Given that the dynamic effects of physical activity, stress experience, and affect on each other were expected to occur within the six hours between the measurement points, and to reduce risk of overparametrization of the VAR-models, a lag of 1 was chosen for all cross-correlations (Brandt & Williams, 2007). For all autocorrelations, a lag of 1 or 2 was chosen dependent on the most optimal model for the participant. The VAR models were fit using the R-package AutovarCore (Emerencia et al., 2016). AutovarCore is an algorithm to automatically estimate vector autoregression (VAR) models for a participant. In our VAR models, we included six endogenous variables: PA high and low arousal, NA high and low arousal, physical activity, and stress experience. Measurement moment was included as an exogenous variable, weekday and study day were modeled if they improved the model for an individual, as well as linear and quadratic trends. Missing data was imputed using the R-package Amelia II, which is a well-validated approach to missing data handling (Honaker & King, 2010). AutovarCore automatically checks assumptions for a VAR model of stability, serial independence, homoscedasticity, and normality of the residuals (Brandt & Williams, 2007; Emerencia et al., 2016); which resulted in 42 valid models (no anhedonia: 22; anhedonia: 20). Two individuals could no longer be matched, resulting in a final sample of 40 individuals; 20 in each group.

Second, our VAR models were analyzed automatically by means of impulse response function analysis (IRF) using the *R*-package AIRA (automated impulse response analysis; Blaauw et al., 2017). VAR models provide an overview of how the modeled time lagged variables are related to each other. However, it is the behavior of the combination of the coefficients (i.e., the model as a whole) that describes the dynamicity of the model (Brandt & Williams, 2007). One way to analyze the model as a whole is by simulating a sudden increase in one variable (or 'shock' in IRF parlance), and investigating how this sudden increase is propagated through the model, i.e., how it affects the other variables both in terms of duration and magnitude. This is known as IRF analysis. IRFs show the hypothetical change in a variable over a horizon of several time points in response to an isolated shock in one of the other variables (see Figure 1 for an example). AIRA performs IRF analysis on each of the variables in the VAR model in isolation to determine how much each variable affects the other variables.

For every person and every association between variables, we calculated cumulative IRFs (Rosmalen et al., 2012), which were constructed by summing all impacts within the horizon of ten time points that are significant (i.e., the confidence interval does not include zero for that particular step, see Figure 1). These individual cumulative IRFs reflect the impact of all variables on each other over time, which was then visualized in 40 individual network models, one for each participant. Next, we constructed *group* cumulative IRFs by summing all individual cumulative IRFs for each association, to enable us to compare the non-anhedonic versus the anhedonic group. This was done separately for individual positive cumulative IRFs and individual negative cumulative IRFs, because combining both would cancel out present associations. Thus, the higher the positive or negative group cumulative IRF, the stronger the impact of one variable on another.

Figure 1. Example of how individual cumulative impulse response functions (IRFs) and group cumulative IRFs are constructed. This figure shows the impact of an impulse in stress experience on NA low arousal, over a horizon of 10 time points, for three hypothetical individuals. Dashed lines indicate the confidence intervals around the IRF. For the first individual, stress experience first increases NA low arousal at step 1-5 (grey transparent area), after which the impact of stress experience on PA high arousal is no longer significant (from step 6 onwards). To construct the individual cumulative IRF for the impact of stress experience on NA low arousal for this individual, the values of step 1-5 are summed. To construct the group cumulative IRF for the impact of stress experience on NA low arousal, the individual cumulative IRFs for all individuals are summed.



We used three approaches to compare emotional dynamics between the non-anhedonic group and the anhedonic group as described above. First, we compared the group cumulative IRFs for each association. Such a comparison would indicate whether the impact of physical activity and stress experience is *stronger* in one of the two groups. Second, we compared the *number* of individuals who showed a given IRF association by examining the individual models. Third, we compared the *importance* of the variables as node in the network by comparing network centrality (node strength) indices between the two groups for each variable. Strength centrality is the sum of the connection strength values (based on the cumulative IRF scores) of all IRF associations that a given variable has within the network (Opsahl, Agneessens, & Skvoretz, 2010). Thus, a high strength centrality of a variable indicates that this variable has a strong impact on other variables or is impacted by many variables. We focused on "outstrength" centrality, which is the total impact of a given variable on all other variables in the network (sum of outgoing cumulative IRF associations). We further examined whether each variable impacted other variables in a favorable manner (resulting in an increase of PA and activity or decrease of NA and stress) or unfavorable manner (resulting in a decrease in PA and activity or an increase in NA and stress).

Finally, we explored individual differences in emotional dynamics displayed in the individual network models. We will depict two of these individual models to illustrate existing individual emotional dynamics and how the use of such personalized networks may possibly inform on choice of intervention type.

Results

Mean levels of affect, stress and activity

Multilevel analyses indicated no significant differences in mean levels of affect, physical activity, and stress experience between the anhedonic group and the non-anhedonic group over the 30-day study period (for the means, standard deviations, and p-values, see Supplementary Table 1). As the groups were matched, level of depression was the same in both groups (mean QIDS score = 9.1; range 6-17), as well as the distribution of gender (19 females and 1 male), and education level (non-anhedonic group: N=17 with higher education; anhedonic group: N=18 with higher education). Groups were of similar age (non-anhedonic: M = 43.6, SD = 13.2; anhedonic: M = 39.5, SD = 11.7, p of difference =.302).

Impact of physical activity and stress experience

Table 1 and Figure 2 show the *strength* of the IRF associations through the group cumulative IRFs, which are composed of the individual cumulative IRFs, split into positive and negative associations for each possible association within the network. It also shows the range in individual cumulative IRFs. Further, it shows the *number* of individuals who showed a particular significant IRF association. Table 2 shows the *importance* of each of the variables in the network.

In both groups, the impact of physical activity on affect was *weak*, as shown by the small positive and negative group cumulative IRFs and the small *number* of individuals with significant IRFs (see Table 1). Further, the groups did not differ on the *importance* of physical activity in the network (non-anhedonic: outstrength = 0.98; anhedonic: outstrength =1.04). In both groups, physical activity seemed to have a more unfavorable (non-anhedonic: unfavorable outstrength = 0.83; anhedonic: unfavorable outstrength = 0.61) than favorable impact (non-anhedonic: favorable outstrength = 0.15; anhedonic: unfavorable outstrength = 0.43) on affect and stress experience (see Table 2).

Table 1. Group cumulative IRF associations per group (*strength*), the *number* of individuals showing a given association significantly, and the range in individual cumulative IRFs

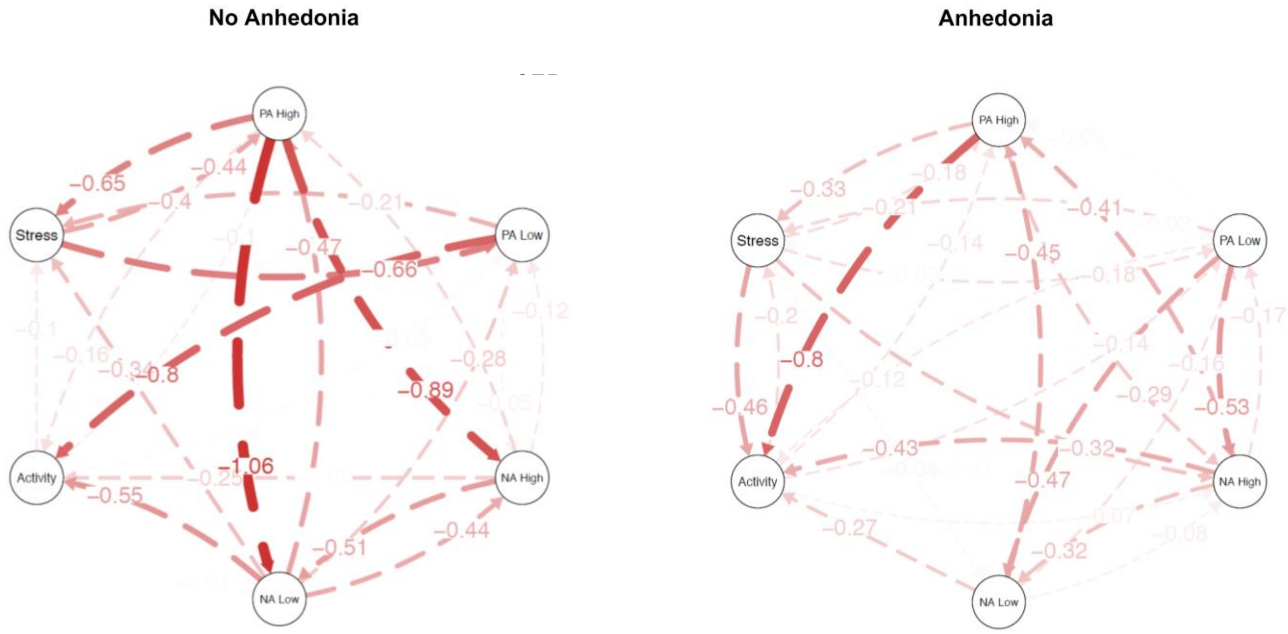
		No anhedonia						**Anhedonia**					
		Positive IRF associations			**Negative IRF associations**			**Positive IRF associations**			**Negative IRF associations**		
Effect of	**On**	**GC IRF**	**N**	**Range**	**GC IRF**	**N**	**Range**	**GC IRF**	**N**	**Range**	**GC IRF**	**N**	**Range**
PA high arousal	PA low arousal	0.51	5	0.05 - 0.25	0.00	0	-	0.58	2	0.05 - 0.53	-0.03	1	-0.03
	NA high arousal	0.00	0	-	-0.89	4	-0.37 - -0.10	0.00	0	-	-0.29	4	-0.13 - -0.004
	NA low arousal	0.00	0	-	-1.06	4	-0.40 - -0.12	0.05	1	0.05	-0.01	1	-0.01
	Physical activity	0.47	2	0.21 - 0.26	-0.16	2	-0.13 - -0.03	0.53	3	0.01 - 0.43	-0.80	2	-0.74 - -0.06
	Stress experience	0.01	1	0.01	-0.65	7	-0.26 - -0.01	0.06	2	0.002 - 0.05	-0.33	2	-0.19 - -0.14
PA low arousal	PA high arousal	0.19	2	0.02 - 0.17	0.00	0	-	0.64	3	0.07 - 0.33	-0.03	1	-0.03
	NA high arousal	0.04	1	0.04	-0.05	1	-0.05	0.02	1	0.02	-0.53	3	-0.33 - -0.06
	NA low arousal	0.18	2	0.05 - 0.13	-0.02	1	-0.02	0.05	1	0.05	-0.47	4	-0.21 - -0.06
	Physical activity	0.31	1	0.31	-0.80	2	-0.78 - -0.02	0.44	2	0.13 - 0.31	-0.12	2	-0.08 - -0.03
	Stress experience	0.00	0	-	-0.40	2	-0.38 - -0.02	0.40	1	0.4	-0.21	3	-0.14 - -0.03
NA high arousal	PA high arousal	0.09	2	0.004 - 0.09	-0.21	2	-0.19 - -0.02	0.22	1	0.22	-0.41	3	-0.27 - -0.002
	PA low arousal	0.01	1	0.01	-0.12	2	-0.11 - -0.008	0.00	0	-	-0.17	1	-0.17
	NA low arousal	0.08	2	0.01 - 0.08	-0.51	4	-0.41 - -0.009	0.32	1	0.32	-0.32	3	-0.13 - -0.06
	Physical activity	0.03	1	0.03	-0.25	1	-0.25	0.00	0	-	-0.43	2	-0.22 - -0.21
	Stress experience	0.21	3	0.02 - 0.13	0.00	0	-	1.33	6	0.08 - 0.39	-0.03	1	-0.03
NA low arousal	PA high arousal	0.08	2	0.001 - 0.08	-0.47	4	-0.30 - -0.02	0.14	2	0.007 - 0.14	-0.45	3	-0.33 - -0.05
	PA low arousal	0.05	2	0.008 - 0.04	-0.28	4	-0.11 - -0.03	0.08	1	0.08	-0.16	2	-0.11 - -0.05
	NA high arousal	0.60	5	0.07 - 0.17	-0.44	2	-0.39 - -0.05	0.10	1	0.1	-0.08	1	-0.08
	Physical activity	0.12	2	0.002 - 0.12	-0.55	3	-0.25 - -0.09	0.30	1	0.3	-0.27	1	-0.27
	Stress experience	0.04	1	0.04	-0.34	2	-0.33 - -0.01	0.36	2	0.04 - 0.32	0.00	0	-
Physical activity	PA high arousal	0.01	2	0.002 - 0.007	-0.10	2	-0.09 - -0.01	0.09	3	0.002 - 0.05	-0.14	1	-0.14
	PA low arousal	0.03	1	0.03	-0.03	4	-0.01 - -0.003	0.07	2	0.01 - 0.06	-0.14	2	-0.11 - -0.04
	NA high arousal	0.17	3	0.005 - 0.14	0.00	0	-	0.14	4	0.02 - 0.04	-0.07	2	-0.05 - -0.02
	NA low arousal	0.10	3	0.02 - 0.05	-0.01	1	-0.01	0.17	2	0.05 - 0.12	0.00	0	-
	Stress experience	0.43	5	0.002 - 0.30	-0.10	2	-0.10 - -0.00008	0.02	2	0.000007 - 0.02	-0.20	3	-0.09 - -0.04
Stress experience	PA high arousal	0.05	2	0.003 - 0.05	-0.44	4	-0.35 - -0.003	0.46	2	0.05 - 0.41	-0.18	4	-0.12 - -0.004
	PA low arousal	0.05	1	0.05	-0.66	3	-0.46 - -0.04	0.53	2	0.04 - 0.49	-0.18	3	-0.16 - -0.002
	NA high arousal	0.24	4	0.009 - 0.21	0.00	0	-	0.01	2	0.004 - 0.01	-0.32	1	-0.32
	NA low arousal	0.94	6	0.006 - 0.27	0.00	0	-	0.19	2	0.03 - 0.16	-0.04	2	-0.04 - -0.008
	Physical activity	0.26	3	0.03 - 0.15	0.00	0		0.00	0	0	-0.46	2	-0.39 - -0.07

Note. Abbreviations: PA = positive affect, NA = negative affect, GC IRF = group cumulative impulse response function

Figure 2. Networks per group showing the *strength* of the IRF associations, by displaying the group cumulative IRFs, i.e., the sum of all positive and negative individual IRF associations of all participants of each group.

Positive IRF Associations

Negative IRF Associations



Note. Each association shown in the group networks reflects the total impact one variable has on another over time for the individuals in that group (group cumulative impulse response function). Green (solid) arrows indicate positive associations between variables, red (dashed) arrows negative ones. The stronger a particular association, the brighter the color of the arrow.

Table 2. Centrality estimates per group showing the *importance* of a variable in the network.

	No anhedonia			**Anhedonia**		
Variable	**Outstrength**			**Outstrength**		
	Total	Favorable	Unfavorable	Total	Favorable	Unfavorable
PA high arousal*	**3.75**	**3.58**	0.17	2.68	1.74	0.94
PA low arousal*	1.99	0.97	1.02	2.91	**2.29**	0.62
NA high arousal	1.51	0.64	0.87	**3.23**	0.57	**2.66**
NA low arousal	2.97	1.03	1.94	1.94	0.6	1.34
Physical activity*	0.98	0.15	0.83	1.04	0.43	0.61
Stress experience	2.64	0.36	**2.28**	2.19	1.35	1.02

Note: * indicates this is considered a positive variable. Bolded numbers reflect the highest estimate per group, indicating that this variable has the strongest impact on all other variables (outstrength). Outstrength was split into favorable and unfavorable impact of the variables. For example, the favorable outstrength of PA high arousal for the non-anhedonic group was constructed by summing all positive group cumulative IRFs for positive variables and all negative group cumulative IRFs for negative variables (0.51 + 0.47 + 0.89 + 1.06 + 0.65 = 3.58, see Table 1).

The unfavorable impact of stress experience on affect was more profound among non-anhedonic individuals compared to anhedonic individuals. For non-anhedonic individuals, an increase in stress experience resulted in more NA high arousal (non-anhedonic: group cumulative IRF = 0.24; anhedonic: group cumulative IRF = 0.01) and more NA low arousal (non-anhedonic: group cumulative IRF = 0.94; anhedonic: group cumulative IRF = 0.19) than for anhedonic individuals. Further, for non-anhedonic individuals, stress experience more strongly decreased PA high arousal (non-anhedonic: group cumulative IRF = -0.44; anhedonic: group cumulative IRF = -0.18) and PA low arousal (non-anhedonic: group cumulative IRF = -0.66; anhedonic: group cumulative IRF = -0.18) than for anhedonic individuals. However, the individual models (see Supplementary Figure 2) show that the *number* of individuals demonstrating an unfavorable impact of stress (i.e., these individuals showed at least one unfavorable IRF association of stress) was similar for both groups (non-anhedonic: N = 7; anhedonic: N = 5). The strong negative impact of stress experience for non-anhedonic individuals is further reflected by their high unfavorable outstrength centrality (see Table 2), which was doubled for anhedonic individuals (non-anhedonic: unfavorable outstrength centrality = 2.28; anhedonic: unfavorable outstrength centrality = 1.02).

Network dynamics: role of other variables

As the other dynamic IRF associations may provide additional insight in the mechanisms underlying anhedonia, we also conducted exploratory analyses to examine the roles of other variables in the network.

For non-anhedonic individuals, PA high arousal showed a favorable impact on the other variables, which was evident in the strength as well as the number and the importance of the impact of PA high arousal. Regarding *strength*, for non-anhedonic individuals, PA high arousal resulted in less NA high arousal (non-anhedonic: group cumulative IRF = -0.89; anhedonic: group cumulative IRF = -0.29), less NA low arousal (non-anhedonic: group cumulative IRF = -1.06; anhedonic: group cumulative IRF = -0.01), and less stress (non-anhedonic: group cumulative IRF = -0.65; anhedonic: group cumulative IRF = -0.33). Further, the individual models show that the *number* of individuals with IRF associations originating from PA high arousal was larger in the non-anhedonic group (non-anhedonic: N = 13, anhedonic: N = 8). Finally, in terms of centrality measures, the favorable outstrength of PA high arousal was more than twice as high for non-anhedonic individuals (non-anhedonic: favorable outstrength = 3.58; anhedonic: favorable outstrength = 1.74) and was by far the most *important* variable in the network.

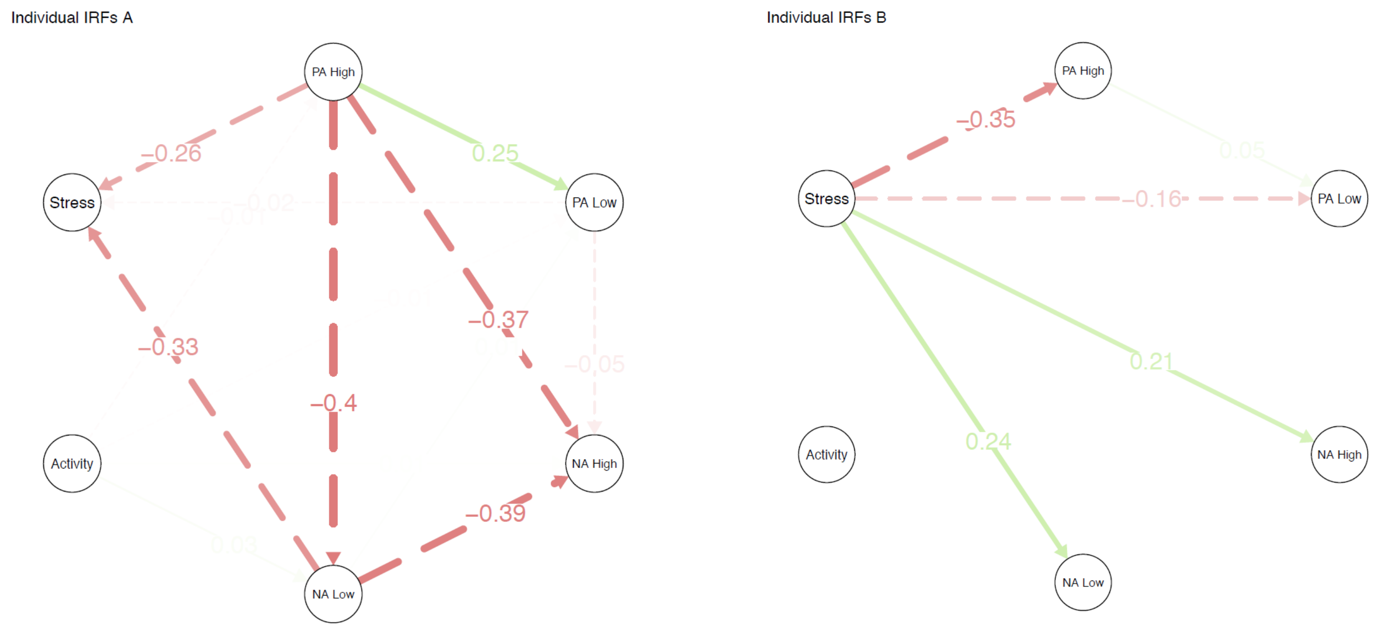
For anhedonic individuals, rather than PA low arousal, PA high arousal showed a favorable impact on the other variables, as indicated in the *strength*, the *number*, and the *importance* of PA low arousal in the network. This indicates that certain positive emotions have a very different role in the network of anhedonic compared to non-anhedonic individuals with depressive symptoms. Further, NA high arousal showed a stronger unfavorable impact on the other variables for anhedonic individuals relative to non-anhedonic individuals. This was reflected in the *strength,* the *number*, and the *importance* of NA high arousal in the network. The strong unfavorable impact of NA high arousal mainly seemed to stem from six individuals showing a strong impact of NA high arousal on stress experience (see Table 1). No other important and consistent patterns emerged from the data.

Exploration of individual networks of emotional dynamics

All individual models per group can be found in Supplementary Figure 2. The individual models reveal large individual differences in the dynamic associations between physical activity, stress experience, and affect within the groups of people with and without anhedonia. Three individuals (non-anhedonic: N = 1; anhedonic: N = 2) had no IRF associations, indicating that their physical activity, stress experience and affect did not have a dynamic impact on each other in these individuals. Nine individuals (non-anhedonic: N = 4; anhedonic: N = 5) only showed one or two IRF associations. Seven individuals (non-anhedonic: N = 3; anhedonic: N = 4) showed ten or more IRF associations.

Figure 3 illustrates an example of two participants who differ in their emotional dynamics. Both individual A and B were non-anhedonic and had equal levels of depression severity (QIDS = 6). However, for individual A, PA high arousal had a strong favorable impact on the other variables in the network (i.e., it decreased NA high and low arousal and stress, and increased PA low arousal). For individual B, stress experience had a strong unfavorable impact on the other variables (i.e., it increased NA high and low arousal, and decreased PA high and low arousal).

Figure 3. Individual IRF networks for two non-anhedonic individuals with equal levels of depression (QIDS = 6), female, who both received higher education. This Figure illustrates that although clinical characteristics are highly similar, emotional dynamics can show very different patterns, warranting a personalized approach to treatment.



Note. Each association shown in the individual networks reflects the total impact one variable has on another over time (individual cumulative impulse response function). Green (solid) arrows indicate positive associations between variables, red (dashed) arrows negative ones. The stronger a particular association, the brighter the color of the arrow.

Discussion

This study investigated the impact of physical activity and stress experience on affect in daily life, and explored other relevant differences in emotional dynamics, in subclinically depressed individuals with anhedonia versus without anhedonia. We used personalized IRFs analyses to study the dynamic impact of the variables on the network as a whole for each individual separately. To our knowledge, this is the first study that maps individual models of the dynamic associations between physical activity, stress, and affect to understand the mechanisms of anhedonia.

Contrary to our hypotheses, the impact of physical activity on affect was low for both anhedonic and non-anhedonic individuals. Thus, when a sudden increase in physical activity was simulated, the other variables only marginally changed in response. Furthermore, also against our expectations, stress experience demonstrated a stronger unfavorable impact on affect in non-anhedonic individuals compared to anhedonic individuals.

In addition, the exploratory analyses revealed that positive affect states played a very different role in the network dynamics of subclinically depressed people with versus without anhedonic complaints: PA high arousal showed a much stronger favorable impact on affect, physical activity and stress experience for non-anhedonic individuals. The finding that positive affect, although present to the same extent in both groups, had a *different dynamic impact* in daily life in the context of anhedonia shines a new light on what anhedonia may represent. Finally, this study reveals the presence of large heterogeneity in emotional dynamics within the anhedonic and non-anhedonic group.

We know of no other studies that examined the effects of physical activity in subclinically depressed individuals with versus without anhedonic symptoms. In depressed individuals, ESM studies have generally shown a favorable effect of physical activity on PA (Mata et al., 2012; Snippe et al., 2016; Wichers et al., 2012). In the present study, the impact of physical activity was surprisingly small for all participants and did not differ between the two groups. However, in line with a previous ESM study, we detected large individual differences in whether this impact was favorable or unfavorable (Stavrakakis et al., 2013). The small impact of physical activity might partially be due to the relatively large time window of six hours between measurements; studies reporting larger effects had less time in between measurements (Mata et al., 2012; Wichers et al., 2012).

Contrary to our expectations, stress showed a more profound unfavorable effect for non-anhedonic individuals: stress more strongly decreased PA and increased NA in this group than in the anhedonic group. In the anhedonic group, this was the other way around: NA high arousal demonstrated a more profound unfavorable impact on stress experience. Thus, in non-anhedonic individuals, stress experience seems to generate NA; whereas in anhedonic individuals, NA seems to generate stress experience. Previous ESM studies have consistently shown that MDD is associated with increased reactivity to stress (Myin-Germeys et al., 2003; Wichers et al., 2009b). The current study builds on these findings by showing that increased stress reactivity is especially profound in subclinically depressed individuals without anhedonic symptoms.

Further, our findings show that even though PA high arousal was experienced to similar extent in the two groups, the impact of PA high arousal on subsequent emotional and behavioral states was considerably lower for individuals with anhedonic symptoms. Research suggests that specifically the high arousal component of PA is associated with readiness for action, motivation, and goal-directed behavior (Bradley & Lang, 2007; Harmon-Jones, Gable, & Price, 2013). The finding that PA high arousal does not have a favorable impact on NA and stress experience may help explain why anhedonic individuals in general tend to show poorer prognosis (Moos & Cronkite, 1999; Wardenaar et al., 2012). By reducing the impact of daily stressors and NA, PA high arousal may constitute a resilience factor that buffers against depressive symptoms. In line with this proposition, previous research has shown that PA may buffer against stress sensitivity (van Winkel et al., 2014).

Together with a close inspection of the individual models, these results may give rise to the hypothesis that different pathways underlie depressive symptoms. The individual models demonstrated that these pathways may be present to different extent in subclinically depressed individuals with and without anhedonia. For some individuals, this pathway may be heightened reactivity to stress or NA, whereas for others, this may be diminished favorable impact of PA. Interestingly, the extent to which these pathways were present differed for the anhedonic group versus the non-anhedonic group. Where more individuals in the anhedonic group showed diminished favorable impact of PA and heightened reactivity to NA, individuals in the non-anhedonic group showed heightened reactivity to stress.

The large heterogeneity in the extent to which these pathways of emotional dynamics were present in individuals suggest that interventions need to be personalized in order to adequately target the relevant pathway for each patient. If specific pathways of emotional dynamics can be linked to different courses of MDD, and if intervening on central nodes is found to be effective, these individual models might guide the clinician towards a more informed choice for effective interventions. For example, for individuals demonstrating deficient PA high arousal dynamics, interventions may focus on enhancing the favorable effects of PA high arousal to render the individual more resilient (Figure 3). For individuals exhibiting strong unfavorable effects of stress experience (or NA high arousal), the clinician may concentrate on strategies to prevent or reduce stress experience, such as through mindfulness techniques. This call for personalized medicine is underscored by studies demonstrating large heterogeneity of MDD (Fried & Nesse, 2015) and strong indications that group-level findings may not generalize to individual patients (Molenaar, 2004). Future studies should reveal whether targeting the most central element of a personalized dynamic network indeed optimizes treatment outcomes.

In order for clinicians to be able to implement this personalized approach to treatment, it is paramount that these complex statistical analyses are automated, so the clinician can easily produce personalized models of emotional dynamics. The *R*-package AIRA automatically generates personalized IRF models, and thus facilitates implementation of these analyses in clinical practice (Blaauw et al., 2017). Although the implementation of personalized networks in clinical practice is yet to receive empirical support, this approach shows promise in making more informed decisions on the focus of treatment.

This study had several notable strengths. First, our ESM design ensured that emotional dynamics were studied ecologically valid, in participants' daily lives and their natural environments. Second, we used a sophisticated and personalized statistical approach, automated IRF analyses (AIRA). Uniquely, AIRA examines the impact of a variable on the network as a whole rather than on distinct variables and offers insight into individual differences in daily dynamics. Third, we distinguished between high and low arousal PA and NA, thereby shedding light on relevant differences in emotional dynamics that have been overlooked in studies excluding the arousal dimension.

However, our findings should also be considered in light of several limitations. First, the presence of anhedonia was indicated by endorsement of the QIDS-item on loss of interest, but the QIDS does not contain an item on the other hallmark of anhedonia, loss of pleasure. Second, our sample is drawn from the general population. Patients with clinical depression or more severe anhedonia may show a different pattern of results than the subclinically depressed individuals under study here. Third, our timeframe of six hours was relatively long, which may explain why the associations under study were only present in a small part of the sample. Fourth, given that our sample consisted mostly of highly educated women, results may not generalize to other populations. Fifth, stress experience was measured indirectly by assessing level of distress, rather than the direct impact of stressors. Thus, where the different role of PA in the anhedonic versus non-anhedonic group stands out more clearly and reliably, it remains difficult to unravel the difference in associations between NA and stress experience between the two groups. Finally, other factors than anhedonia may also explain the differences found between the anhedonic and non-anhedonic group, such as the presence of sad mood. Future studies may use a 2 by 2 design focusing on the two core symptoms of depression to fully disentangle their influence on emotional dynamics.

Our results suggest different emotional dynamics may underlie depressive symptomatology. Subclinically depressed individuals with anhedonic complaints may be characterized by lowered favorable impact of PA high arousal on affect and behavior, and heightened reactivity to NA. On the other hand, subclinically depressed individuals without anhedonic complaints may be characterized by heightened stress reactivity. The large heterogeneity in the extent to which these pathways were present in individuals advocates a personalized approach to gain insight in how depressive symptomatology is maintained in daily life. Future studies may relate different pathways of emotional dynamics to future course of depression.

Acknowledgements

This manuscript has received funding from the European Research Council (ERC) under the European Union 2020 research and innovative programme (ERC-CoG-2015; no 681466) to M. Wichers, a VICI grant from the Netherlands Organisation for Scientific Research (NWO/ZonMW no 91812607) to P. de Jonge, and an unrestricted grant from Espria, a healthcare group in the Netherlands consisting of multiple companies targeted mainly at the elderly population.

Conflicts of interest: none

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