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

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29 Abstract

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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

58

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

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

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

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

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

99

100 *Aims of the study*

101 The present study aimed to examine emotional dynamics in the flow of daily life in subclinically
102 depressed individuals with versus without anhedonic symptoms. Specifically, we will study the possibly
103 differential impact of physical activity and stress experience on positive and negative affect in
104 subclinically depressed individuals with versus without anhedonic symptoms. Such an investigation in
105 a general population sample can be the starting point to investigate micro-level dynamics that may
106 underlie the future development of clinical symptoms. These dynamics can be optimally measured
107 through the ecologically valid experience sampling method (ESM, Reis, 2012). With ESM, individuals
108 can record their affect, stress level, and level of physical activity multiple times a day in their own
109 environments (Myin-Germeys, 2012; Shiffman, Stone, & Hufford, 2008), to prospectively examine
110 emotional responses to physical activity and the experience of stress. We will use an advanced extension
111 of vector autoregressive (VAR) modelling called impulse-response function (IRF) analysis (Brandt &
112 Williams, 2007; Lütkepohl, 2005) to compare the impact of a hypothetical increase in physical activity

113 or stress experience on affect for both subgroups. To this end, we used automated impulse-response
114 analysis (AIRA), a novel and sophisticated *R*-package that automates IRF analyses (Blaauw, van der
115 Krieke, Emerencia, Aiello, & de Jonge, 2017). AIRA estimates network models for each individual,
116 after which these models can be combined into aggregated models to compare the two groups. This
117 approach accounts for and offers insight into individual differences in daily dynamics and depressogenic
118 mechanisms.

119

121

122 **Participants**

123 Participants are 629 individuals from the general Dutch population who participated in an ESM protocol
124 of the study “HowNutsAreTheDutch?” (Dutch: HoeGekIsNL?) between May 22nd, 2014 and December
125 13th, 2014 (end of the first-year wave of the website; van der Krieke, Jeronimus et al., 2016; van der
126 Krieke, Blaauw et al., 2016). In order to be included, participants had to indicate they (1) were at least
127 18 years of age, (2) could start with the study within five days (3) possessed a smartphone with a mobile
128 internet connection, (4) were not engaged in shift work, (5) did not anticipate a major disruption of daily
129 routines within the study period, (6) were aware that their results would be useless if too many
130 assessments were missed, and (7) consented to having their anonymous data used for research purposes.

131 For the present paper, we selected individuals who (1) were at least mildly depressed, as
132 indicated by a Quick Inventory for Depressive Symptomatology (QIDS-SR; Rush et al., 2003) score of
133 6 or higher, and (2) completed at least 67 (75%) of the diary assessments (for a flow-chart, see
134 Supplementary Figure 1). Given that anhedonia is defined as loss of interest or pleasure, we used the
135 QIDS-SR item on loss of interest (“I notice that I am less interested in people or activities”) as a proxy
136 for anhedonia. Although this is a single item, this item seems to be a relatively valid measure of
137 anhedonia given its high correlates to anhedonia items of Depression and Anxiety Stress Scales (DASS,
138 Lovibond & Lovibond, 1995). In the HowNutsAreTheDutch sample (N=8575), the QIDS-SR loss of
139 interest item correlated 0.74 with the more general loss of interest item of the DASS (Wardenaar et al.
140 2017) and 0.66-0.70 with the three DASS items on anhedonia (on enjoyment, experience of positive
141 affect, and enthusiasm). Participants who endorsed this item (scored at least ‘1’) are henceforth referred
142 to as ‘anhedonic’, participants who reported no loss of interest as ‘non-anhedonic’. All anhedonic
143 individuals were matched to non-anhedonic individuals based on their QIDS-SR score, sex, and
144 education level, respectively. This resulted in 50 matched individuals, 25 in each group.

145

146 **Measures**

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

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

164

165 **Analyses**

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

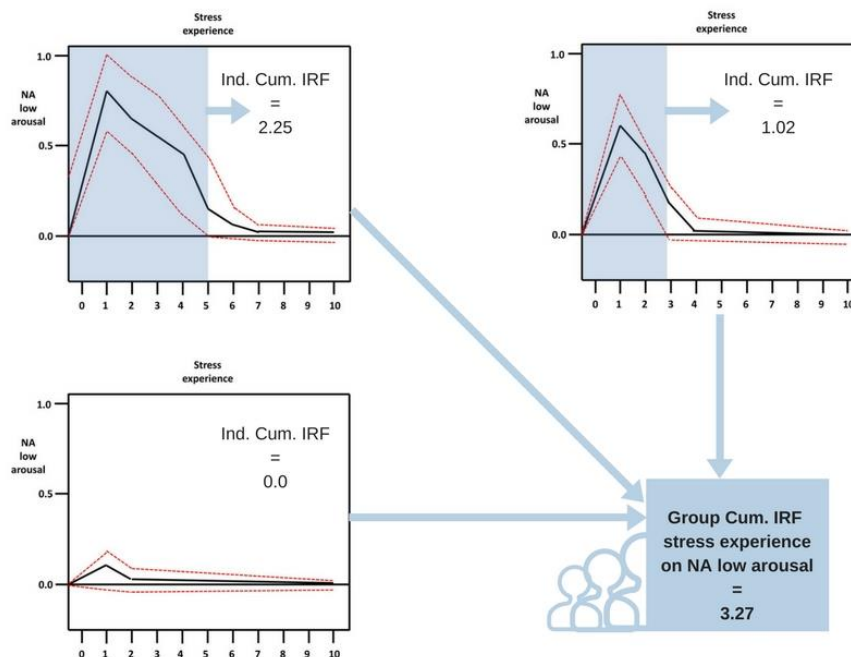
172 First, we fitted a vector autoregression (VAR) model for every participant. In a VAR model,
173 each variable is regressed on its own lagged values (autocorrelation) as well as the lagged values of the
174 other variables (Brandt & Williams, 2007), resulting in a set of regression coefficients for each

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

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

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

213
 214 Figure 1. Example of how individual cumulative impulse response functions (IRFs) and group
 215 cumulative IRFs are constructed. This figure shows the impact of an impulse in stress experience on NA
 216 low arousal, over a horizon of 10 time points, for three hypothetical individuals. Dashed lines indicate
 217 the confidence intervals around the IRF. For the first individual, stress experience first increases NA
 218 low arousal at step 1-5 (grey transparent area), after which the impact of stress experience on PA high
 219 arousal is no longer significant (from step 6 onwards). To construct the individual cumulative IRF for
 220 the impact of stress experience on NA low arousal for this individual, the values of step 1-5 are summed.
 221 To construct the group cumulative IRF for the impact of stress experience on NA low arousal, the
 222 individual cumulative IRFs for all individuals are summed.
 223



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

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

243

244

245

246 Mean levels of affect, stress and activity

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

254

255 Impact of physical activity and stress experience

256 Table 1 and Figure 2 show the *strength* of the IRF associations through the group cumulative IRFs,
257 which are composed of the individual cumulative IRFs, split into positive and negative associations for
258 each possible association within the network. It also shows the range in individual cumulative IRFs.
259 Further, it shows the *number* of individuals who showed a particular significant IRF association. Table
260 2 shows the *importance* of each of the variables in the network.

261 In both groups, the impact of physical activity on affect was *weak*, as shown by the small positive
262 and negative group cumulative IRFs and the small *number* of individuals with significant IRFs (see
263 Table 1). Further, the groups did not differ on the *importance* of physical activity in the network (non-
264 anhedonic: outstrength = 0.98; anhedonic: outstrength = 1.04). In both groups, physical activity seemed
265 to have a more unfavorable (non-anhedonic: unfavorable outstrength = 0.83; anhedonic: unfavorable
266 outstrength = 0.61) than favorable impact (non-anhedonic: favorable outstrength = 0.15; anhedonic:
267 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

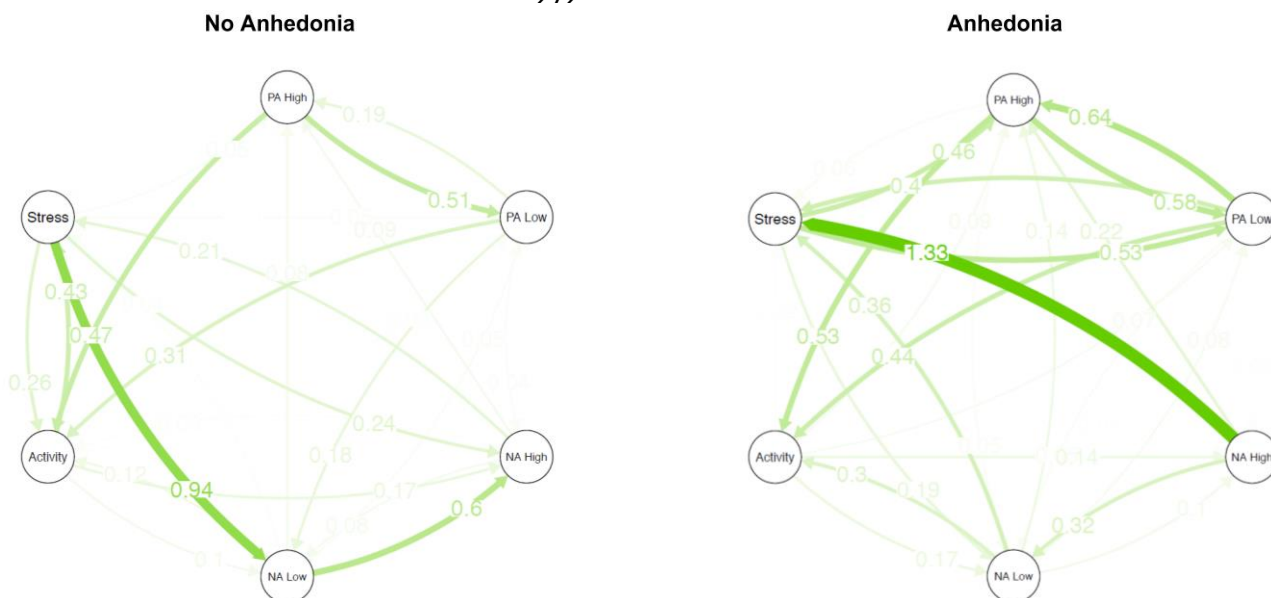
Note. Abbreviations: PA = positive affect, NA = negative affect, GC IRF = group cumulative impulse response function

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

271

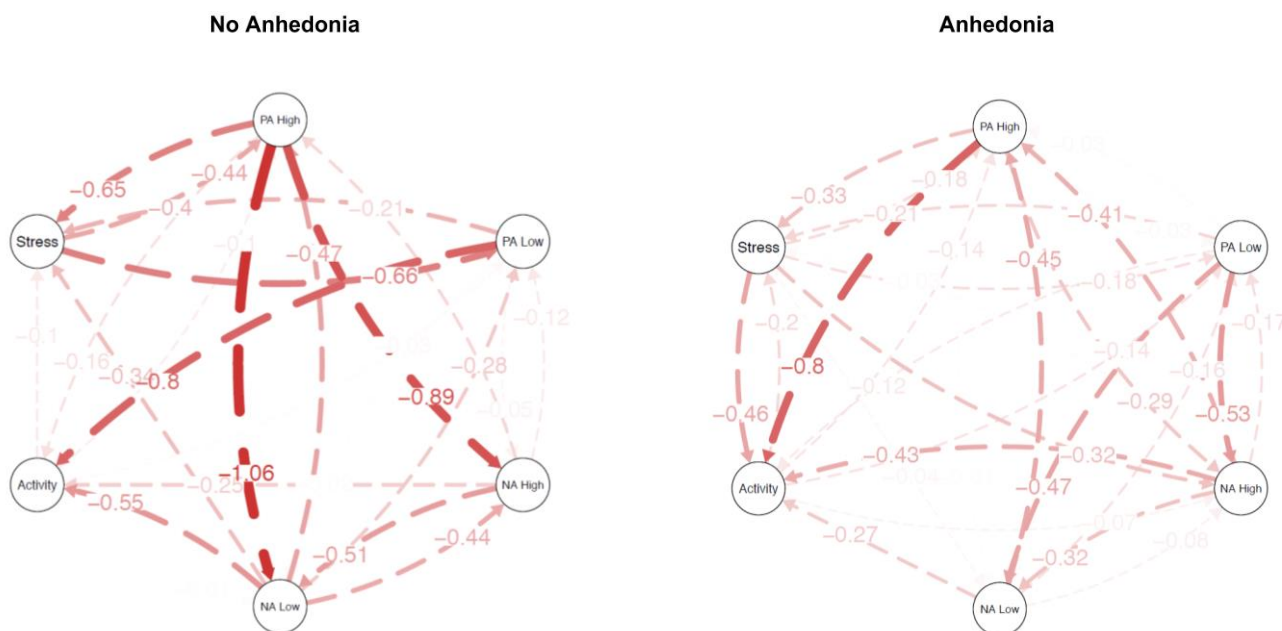
Positive IRF Associations

272



273

Negative IRF Associations



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

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

Variable	No anhedonia			Anhedonia		
	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

289 *Note:* * indicates this is considered a positive variable. Bolded numbers reflect the highest estimate per group,
 290 indicating that this variable has the strongest impact on all other variables (outstrength). Outstrength was split into
 291 favorable and unfavorable impact of the variables. For example, the favorable outstrength of PA high arousal for
 292 the non-anhedonic group was constructed by summing all positive group cumulative IRFs for positive variables
 293 and all negative group cumulative IRFs for negative variables ($0.51 + 0.47 + 0.89 + 1.06 + 0.65 = 3.58$, see Table
 294 1).

295

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

311

312 **Network dynamics: role of other variables**

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

316 For non-anhedonic individuals, PA high arousal showed a favorable impact on the other
317 variables, which was evident in the strength as well as the number and the importance of the impact of
318 PA high arousal. Regarding *strength*, for non-anhedonic individuals, PA high arousal resulted in less
319 NA high arousal (non-anhedonic: group cumulative IRF = -0.89; anhedonic: group cumulative IRF = -
320 0.29), less NA low arousal (non-anhedonic: group cumulative IRF = -1.06; anhedonic: group cumulative
321 IRF = -0.01), and less stress (non-anhedonic: group cumulative IRF = -0.65; anhedonic: group
322 cumulative IRF = -0.33). Further, the individual models show that the *number* of individuals with IRF
323 associations originating from PA high arousal was larger in the non-anhedonic group (non-anhedonic:
324 N = 13, anhedonic: N = 8). Finally, in terms of centrality measures, the favorable outstrength of PA high
325 arousal was more than twice as high for non-anhedonic individuals (non-anhedonic: favorable
326 outstrength = 3.58; anhedonic: favorable outstrength = 1.74) and was by far the most *important* variable
327 in the network.

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

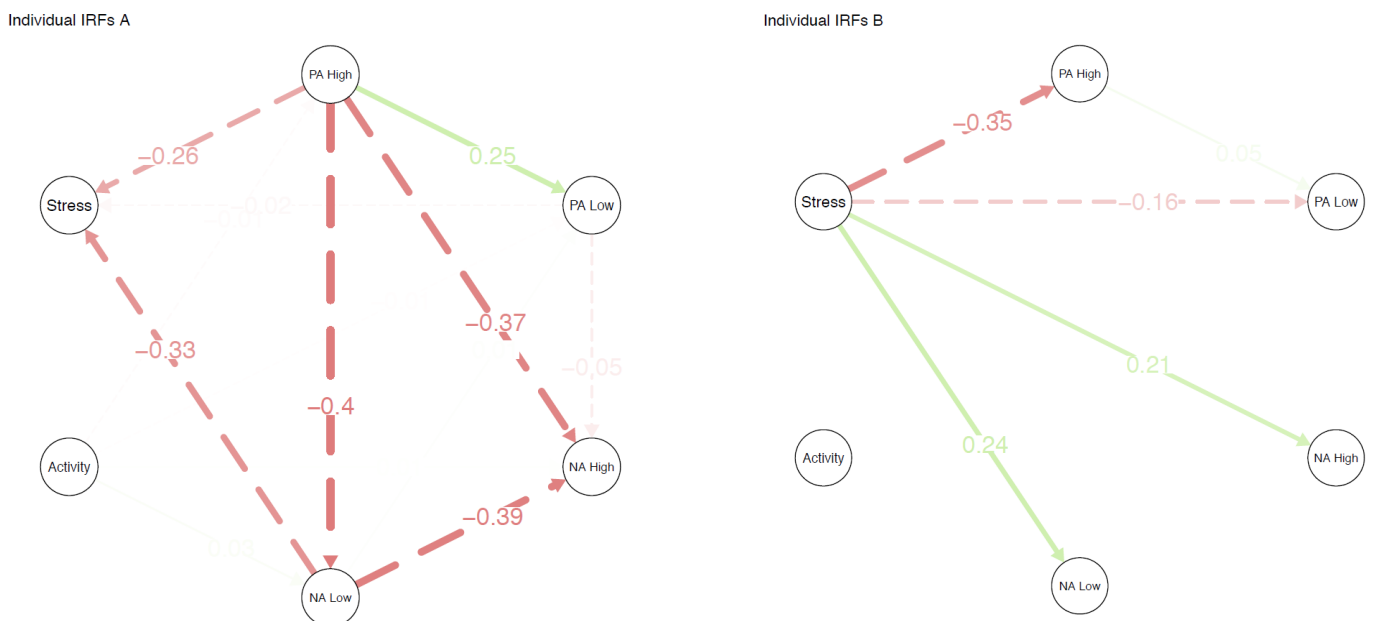
337

338 **Exploration of individual networks of emotional dynamics**

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

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

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



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

Discussion

360

361

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

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

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

380 We know of no other studies that examined the effects of physical activity in subclinically
381 depressed individuals with versus without anhedonic symptoms. In depressed individuals, ESM studies
382 have generally shown a favorable effect of physical activity on PA (Mata et al., 2012; Snippe et al.,
383 2016; Wichers et al., 2012). In the present study, the impact of physical activity was surprisingly small
384 for all participants and did not differ between the two groups. However, in line with a previous ESM
385 study, we detected large individual differences in whether this impact was favorable or unfavorable
386 (Stavrakakis et al., 2013). The small impact of physical activity might partially be due to the relatively

387 large time window of six hours between measurements; studies reporting larger effects had less time in
388 between measurements (Mata et al., 2012; Wichers et al., 2012).

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

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

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

414 more individuals in the anhedonic group showed diminished favorable impact of PA and heightened
415 reactivity to NA, individuals in the non-anhedonic group showed heightened reactivity to stress.

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

429 In order for clinicians to be able to implement this personalized approach to treatment, it is
430 paramount that these complex statistical analyses are automated, so the clinician can easily produce
431 personalized models of emotional dynamics. The *R*-package AIRA automatically generates personalized
432 IRF models, and thus facilitates implementation of these analyses in clinical practice (Blaauw et al.,
433 2017). Although the implementation of personalized networks in clinical practice is yet to receive
434 empirical support, this approach shows promise in making more informed decisions on the focus of
435 treatment.

436 This study had several notable strengths. First, our ESM design ensured that emotional dynamics
437 were studied ecologically valid, in participants' daily lives and their natural environments. Second, we
438 used a sophisticated and personalized statistical approach, automated IRF analyses (AIRA). Uniquely,
439 AIRA examines the impact of a variable on the network as a whole rather than on distinct variables and
440 offers insight into individual differences in daily dynamics. Third, we distinguished between high and

441 low arousal PA and NA, thereby shedding light on relevant differences in emotional dynamics that have
442 been overlooked in studies excluding the arousal dimension.

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

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

466

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467

468

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474

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