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# Blunted cardiovascular reactivity during social reward anticipation in subclinical depression

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#### Abstract

The present study extends past research about reduced reward responsiveness in depression by assessing effort-related cardiovascular responses during anticipation of a social reward. Dysphoric (i.e., subclinically depressed) and nondysphoric participants worked on a cognitive task. Half the participants in each group expected the possibility to subscribe to a social exchange internet site. Effort mobilization during task performance was assessed by participants' cardiovascular reactivity. Confirming the predictions, nondysphoric participants in the social-reward condition had higher reactivity of pre-ejection period, systolic blood pressure, and heart rate, compared to the other three cells. In contrast, dysphoric participants' cardiovascular reactivity was generally low. These findings indicate that social-reward function is indeed impaired in subclinical depression. Implications for social punishment are discussed.

Keywords: depression; dysphoria; effort mobilization; cardiovascular reactivity; social reward; reward anticipation;

# Blunted cardiovascular reactivity during social reward anticipation in subclinical depression

### **1. Introduction**

# 1.1 Reward responsiveness in depression

Depression is a high-prevalence disorder (Kessler and Wang, 2009), which is characterized, amongst others, by reduced responsiveness to rewards (for reviews see Eshel and Roiser, 2010; Pizzagalli et al., 2011). The wealth of empirical studies strongly suggest that individuals with clinical and subclinical depression are impaired in their response to rewards both during the anticipatory (i.e., motivational) phase and during the consummatory (i.e., emotional) phase (for a detailed discussion about the distinction between these two phases, see Berridge and Robinson, 2003; Gard et al., 2006). Specifically, depressed individuals report less anticipated pleasure (e.g., Chentsova-Dutton and Hanley, 2010), show impaired reward-learning behavior (e.g., Huys et al., 2013; Liu et al., 2011; Vrieze et al., 2013), demonstrate impaired reward-related decision making (e.g., Kunisato et al., 2012; Treadway et al., 2012), have reduced activity in approach-related cortical regions (e.g., Shankman et al., 2013; for a review see Thibodeau et al., 2006), and show altered activity in reward-related brain regions (for a review see Zhang et al., 2013). Recently, we have shown reduced effort-related cardiovascular reactivity during goal pursuit in subclinical depression (Brinkmann and Franzen, 2013; Brinkmann et al., 2009; Franzen and Brinkmann, 2015, 2016a).

#### 1.2 Social rewards in depression

The great majority of this converging literature has relied on monetary rewards, which have universal significance and which are easy to quantify and apply. Recently, arguments have been advanced that social rewards might be more meaningful but also especially affected in depression (Forbes, 2009; Forbes and Dahl, 2012). However, their role has not been fully understood. To date, a couple of studies have demonstrated associations between depression and reduced neural responses during the viewing of pleasant facial expressions and words (Epstein et al., 2006; Monk et al., 2008; Surguladze et al., 2005) and during the sight and taste of pleasant chocolate stimuli (McCabe et al., 2009; McCabe et al., 2012). These findings point to the general nature of reduced reward responsiveness in depression, beyond monetary rewards.

With respect to social rewards in particular, three neuro-imaging studies have shown altered responsiveness in reward-related brain areas of depressed and high-risk individuals

during the consummatory phase (Davey et al., 2011; Healey et al., 2014; Olino et al., 2015). In these studies, social reward consumption has been operationalized by receiving positive social feedback, by viewing pictures of peers who returned participants' liking, and by being accepted by a previously liked peer. However, these studies are limited in their focus on participants' neural response during the consummatory phase. From a motivational point of view, it would be informative to know whether or not depressed individuals mobilize more effort or achieve better results when anticipating a positive social consequence.

Only two recent studies have investigated behavior and effort mobilization during social reward anticipation. One study revealed that remitted depressed individuals show impaired reward-learning when expecting social praise as reward feedback for correct responses (Pechtel et al., 2013). Another study demonstrated that dysphoric (i.e., subclinically depressed) participants mobilize less effort when expecting social approval in form of the possibility to enter one's name in a public "best list" (Brinkmann et al., 2014). Specifically, reduced effort mobilization was evidenced by a weaker response of systolic blood pressure (SBP) during task performance.

## 1.3 Effort mobilization and cardiovascular response

Effort mobilization refers to the resources a person is mobilizing at a point in time in order to carry out a certain behavior (Gendolla and Wright, 2009). Effort-related cardiovascular response is an important peripheral measure that directly relates to the anticipatory, motivational phase of reward processing. It provides information about the vigor with which individuals pursue their goals. The integrative approach by Wright (1996) brings together the predictions of motivational intensity theory (Brehm and Self, 1989) with considerations about psychophysiological responses in active coping situations (Obrist, 1981). Specifically, Wright argued that effort mobilization during goal pursuit can be operationalized by cardiovascular parameters that are influenced by beta-adrenergic sympathetic nervous system (SNS) impact on the heart.

Among the most common noninvasive cardiovascular parameters is the pre-ejection period (PEP). PEP refers to the time interval between the onset of left ventricular excitation and the opening of the heart's aortic valve. This cardiovascular parameter is a reliable and direct measure of the force of myocardial contraction, which is determined by beta-adrenergic SNS impact on the heart (Kelsey, 2012; Sherwood et al., 1990). Other common cardiovascular parameters include systolic blood pressure (SBP) and diastolic blood pressure (DBP). SBP strongly depends on the force of myocardial contraction and to a lesser extent on vascular resistance. Whereas the impact of myocardial contraction via its impact on cardiac output is mainly mediated by beta-adrenergic SNS activation, the impact of vascular resistance is mainly mediated by alpha-adrenergic SNS activation. In contrast, DBP is predominantly determined by vascular resistance and therefore mainly by alpha-adrenergic SNS activation. Finally, heart rate (HR) is determined by both sympathetic and parasympathetic activation and is therefore not an unambiguous indicator of beta-adrenergic SNS activation (Berntson et al., 1993; Brownley et al., 2000; Levick, 2003; Papillo and Shapiro, 1990). Taken together, PEP can be considered a reliable means for operationalizing effort mobilization (Kelsey, 2012; Wright, 1996). SBP qualifies as a secondary measures of effort mobilization that has been successfully used in the framework of motivational intensity theory, whereas the evidence for DBP and HR is mixed (for reviews see Gendolla, Brinkmann, et al., 2012; Gendolla, Wright, et al., 2012).

According to motivational intensity theory (Brehm and Self, 1989), rewards should have a direct impact on effort mobilization, that is, on cardiovascular reactivity, when task difficulty is fixed but unknown to the performing individuals (termed "unclear difficulty"). Under these circumstances, they cannot adjust their effort mobilization with respect to task difficulty but must rely on the importance of success. In other words, the higher the reward at stake, the more important is success and, therefore, the higher is the effort people mobilize (Richter, 2012; for a more detailed discussion of motivational intensity theory and its predictions see Richter, 2013; Richter et al., 2016). Using tasks with unclear difficulty, several studies have demonstrated that clinically and subclinically depressed individuals show weaker cardiovascular responses during the execution of cognitive tasks, which are instrumental to obtain a monetary reward (Brinkmann and Franzen, 2013; Brinkmann et al., 2009; Franzen and Brinkmann, 2015, 2016b; Franzen et al., 2016). At least two processes are possibly involved in causing reduced effort-related cardiovascular reactivity by depressed individuals in this situation. First, due to mood-congruency biases, rewards are undervalued and do not increase success importance. Second, external control perceptions lead to reduced instrumentality of effort mobilization for obtaining rewards (Franzen and Brinkmann, 2016b).

## 1.4 The present study

To date, one study has demonstrated blunted SBP reactivity in subclinically depressed individuals during the anticipation of a social reward (Brinkmann et al., 2014). The aim of the present study was to conduct a conceptual replication of the Brinkmann et al. study to answer the remaining open questions. First, effort-related cardiovascular reactivity informs about the vigor with which individuals pursue their goals and helps drawing a complete picture of depressed individuals' behavior in a reward situation. The present study is the first one

focusing on PEP as the most direct, noninvasive cardiovascular indicator of effort mobilization in a social reward situation. Second, social reward function in depression has not received much attention, and social reward is not a unitary concept. In the present study we use a more active kind of social reward in order to vary and diversify the types of social rewards and to be able to draw general conclusions about social reward function in depression.

In the present study, we asked dysphoric (i.e., subclinically depressed) and nondysphoric students to perform a mental arithmetic task under unclear-difficulty instructions. Half of the participants worked on the task expecting no specific consequence of their performance (no-reward condition). The other half of the participants were led to believe that, in case they met the performance standard, they could subscribe to a new internet site, as described in more detail below (social-reward condition). We expected a dysphoria x reward interaction effect describing a 3:1 pattern. Specifically, we hypothesized that nondysphoric participants in the social-reward condition would show higher PEP reactivity, reflecting higher effort mobilization, than nondysphoric participants in the no-reward condition and than dysphoric participants in either condition. We expected the same 3:1 pattern for SBP reactivity as a secondary dependent variable. We also assessed DBP and HR, mainly for the interpretability of the PEP pattern, as will be presented in the discussion section (Obrist et al., 1987). Finally, we predicted that nondysphoric participants in the social-reward condition would report higher success importance and higher motivation to obtain the reward than the three other groups.

# 2. Methods

#### 2.1 Participants and design

The present study was a 2 (dysphoric vs. nondysphoric) x 2 (no reward vs. social reward) between-persons design. After having obtained approval of the protocol by the local ethical committee, we recruited students of the University of Geneva with various majors by blackboards advertisements. Participants filled in an online version of the Center for Epidemiologic Studies – Depression Scale (CES-D; Radloff, 1977). Among participants, we invited those who scored in the lower quartile ( $\leq 9$ ) or in the upper quartile ( $\geq 17$ ) of the distribution via an anonymous code. One month later, these students participated in the experimental session in exchange for 15 Swiss Francs (about 15 USD) and were randomly assigned to one of the two reward conditions. From the 88 participants, we excluded data of 19 participants whose CES-D scores did not stay within the limits ( $\leq 9$  or  $\geq 17$ ) when assessed

a second time during the experimental session. Moreover, we removed data of 3 participants whose impedance cardiograms could not be analyzed due to bad signal quality.

The final sample consisted of 66 students with a mean age of 24.02 years, SD = 4.93. Thirty-three participants were located in the upper quartile of the CES-D score distribution (M = 27.18, SD = 8.10, range = 17-45) and were referred to as dysphoric. The remaining 33 participants were situated in the lower quartile of the CES-D (M = 4.64, SD = 2.47, range = 1-9) and were referred to as nondysphoric. Cell distribution was as follows: nondysphoric / no reward: 16 (8 men); nondysphoric / social reward: 17 (6 men); dysphoric / no reward: 17 (4 men); dysphoric / social reward: 16 (7 men).

#### 2.2 Procedure, experimental task and manipulation

The individual experimental sessions took about 35 minutes and used experimental software Inquisit 3.0 (Millisecond Software, Seattle, WA). The experimenter—who was blind to hypotheses and to participants' dysphoria group—welcomed and seated the participants. She explained the two allegedly unrelated parts, the first one being a short questionnaire validation study, and the second one being a study about physiological response at rest and during a cognitive task. After having obtained informed consent, the experimenter attached the physiological recordings material as described below, started the experimental software, left the room, and monitored the experiment from an outside control room. Participants first completed the CES-D, followed by the Temporal Experience of Pleasure Scale (TEPS; Gard et al., 2006), which served for the cover story and was not analyzed for the present study aim.

The main part started with introductory information and some biographic questions. Then, participants watched an 8-min excerpt of a hedonically neutral documentary film, which served as a habituation period for cardiovascular baseline measures. After the habituation period, participants received instructions for the cognitive task, which was a mental arithmetic task with unclear task difficulty. For each trial, an equation (e.g., 6+5+7=18) was briefly presented in the center of the screen. After the equation had disappeared, participants indicated whether or not the equation was correct. If participants answered within 3 sec, the message "answer recorded" was presented on the screen for the remaining time of the 3 sec plus 1 sec. If participants had not responded within 3 sec, the message "please answer more quickly" was displayed for 1 sec. This procedure ensured that trial duration was not influenced by individual reaction times. Each trial including a 1-sec fixation cross lasted 6 or 9 sec, depending on the presentation time of the equation. Instructions explained that the type of equation and their presentation time would vary in a random manner. In order to keep task difficulty unclear, participants did not receive

information about the total time of the task, nor about the difficulty and the presentation time of the equations. In fact, the 5-min task consisted of 20 correct and 20 incorrect equations. The equations varied in type (addition or subtraction), difficulty (2 or 3 numbers) and presentation time (1 or 4 sec), making it impossible to predict the difficulty of the upcoming trial.

After task instructions, participants in the social-reward condition received reward information. They learned that in case their performance met or exceeded the predefined standard they would have the option to subscribe to a new internet site by our laboratory. The aim of the internet site was described as getting information about upcoming experiments and their modalities and, in particular, as having the possibility to exchange with other participants and by this way getting even more information. The subscription was described as free of charge, completely anonymous, and revocable at any time. To keep task difficulty unclear, the standard was not specified, so that participants could not know which score they had to achieve. In fact, there was no such internet site. The standard was created individually by the experimental software by adding 3 to the participant's real performance score, so that nobody could subscribe to the internet site.

Following task and reward information, participants answered two questions evaluating success importance, as described below. Participants in the social reward condition furthermore indicated how motivated they were to subscribe to the internet site. Then the 5min performance period started, during which cardiovascular activity was assessed. At the end of the task, the individual performance score (i.e., number of correct responses) appeared on the screen. In the reward condition, participants were informed about the allegedly predefined standard, which they had failed to meet, and that consequently they could not subscribe to the internet site. At this point, the experimenter returned to the room, thanked and debriefed participants, removed the physiological recordings material, and handed out the promised payment.

#### 2.3 Cardiovascular measures

Cardiovascular measures were collected noninvasively during the habituation period and during task performance. PEP (in milliseconds [ms]) and HR (in beats per minute [bpm]) were measured using a Cardioscreen® 1000 haemodynamic monitoring-system (medis, Ilmenau, Germany) (for a validation study see Scherhag et al., 2005). This system continuously samples electrocardiogram (ECG) and impedance cardiogram (ICG) signals at 1000 Hz and uses four dual gel-pad sensors (medis-ZTECT<sup>TM</sup>). These were placed on each side of the base of the participant's neck and on each side of the thorax at the level of the xiphoid. SBP (in millimeters of mercury [mmHg]) and DBP (in millimeters of mercury [mmHg]) were measured noninvasively using a Dinamap Procare 300 monitor (GE Medical Systems, Information Technologies Inc., Milwaukee, WI), which uses the oscillometric method to determine arterial blood pressure. A blood pressure cuff was placed over the brachial artery above the elbow of participants' nondominant arm and automatically inflated every minute.

## 2.4 Self-report measures

We measured depressive symptomatology by means of the CES-D—a 20-items, self-report depression scale for community samples (French version by Fuhrer and Rouillon, 1989). Participants indicate the frequency of depressive symptom occurrence during the past week on 4-point scales from 0 (*never, very seldom*) to 3 (*frequently, always*). The total score is calculated by summing all negative and reverse-scored positive items and varies from 0 to 60 (Cronbach's  $\alpha$  at the experimental session = .95).<sup>1</sup>

In order to assess the impact of our reward manipulation and to ensure that the social reward was salient (see Richter, 2010), we asked all participants to indicate their perception of success importance ("How important is it for you to succeed in the task?"; "How satisfied will you be after successful task performance?") on 7-point scales ranging from 1 (*not at all*) to 7 (*very much*). These two questions were positively correlated, r(66) = .69, p < .001, and merged into a mean score of success importance. Furthermore, participants in the social-reward condition indicated to what extent they were motivated to subscribe to the internet site on a visual analogue scale from 0 (*not motivated*) to 100 (*very motivated*).

#### 2.5 Data reduction and analysis

HR (in beats per min [bpm]) was determined by means of a software developed in our laboratory (Bluebox 2; Richter, 2014). This software is based on the LabVIEW package (National Instruments, Austin, TX) and detects and counts R-peaks in the ECG signal. Data were also visually inspected and edited for ectopic heart beats. For PEP measures (in ms), the ICG dZ/dt signal (first derivative) was ensemble-averaged over 60-s time intervals. Only valid cycles were included in ensemble averages. The ECG R-onset and the ICG B-point were automatically detected by the same software, visually inspected by two independent trained raters, and modified if necessary (Sherwood et al., 1990). PEP was then calculated as the interval between ECG R-onset and ICG B-point (Berntson et al., 2004). As inter-rater reliability was high, ICC(2, 1) = .91 (Shrout and Fleiss, 1979), the averaged PEP values from

both raters were used for analyses. SBP and DBP raw values (one per minute) were used without further editing.

Cardiovascular baseline scores were determined by averaging the last 4 min of the habituation period (Cronbach's  $\alpha$ s > .97). Task scores were determined by averaging the 5 min of the performance period (Cronbach's  $\alpha$ s > .97). We then calculated cardiovascular reactivity scores by subtracting baseline scores from task scores (Cronbach's  $\alpha$ s > .87) (Kelsey et al., 2007; Llabre et al., 1991).

We submitted cardiovascular baseline values and task performance indices to 2 (dysphoric vs. nondysphoric) x 2 (experimental condition: no reward vs. social reward) between-persons ANOVAs. For the specific analysis of cardiovascular reactivity during task performance and of self-reported success importance, we calculated a priori contrasts (see Rosenthal and Rosnow, 1985). These contrasts enabled us to test with one single test our predicted 3:1 pattern, which stipulates higher cardiovascular reactivity of nondysphoric participants in the social-reward condition compared to the three other conditions. Moreover, these a priori contrasts enabled us to model reduced responsiveness in dysphoric participants by assigning the same contrast weights to both conditions, thereby avoiding the problem of testing a null hypothesis. Consequently, contrast weights were -1 for dysphorics in both conditions and for nondysphorics in the no-reward condition. Nondysphorics in the socialreward condition were assigned a contrast weight of +3. The a priori contrasts were complemented by follow-up cell comparisons using Tukey's HSD procedure. Finally, we calculated an independent-samples *t*-test for comparing dysphoric and nondysphoric participants' self-reported motivation in the reward condition. The a priori level of significance for all tests was set at p < .05 (two-tailed).

# 3. Results

#### 3.1 Cardiovascular baselines

Means and standard errors of cardiovascular baseline values are displayed in Table 1. Results of 2 (dysphoria) x 2 (experimental condition) ANOVAs revealed no significant main or interaction effects for PEP, SBP, and DBP baseline values, F(1, 62)s < 3.96, ps > .05. For HR there was a significant condition main effect, F(1, 62) = 6.23, p = .02,  $\eta^2_p = .09$ , qualified by a significant dysphoria x condition interaction, F(1, 62) = 4.44, p = .04,  $\eta^2_p = .07$ . The dysphoria main effect was not significant, F(1, 62) = 0.17, p = .68. As HR baseline values did not significantly correlate with HR reactivity, r(66) = -.11, p = .39, and in light of the quasiexperimental study design (see Jamieson, 2004), we did not adjust HR reactivity with respect to HR baseline values.

## 3.2 Pre-ejection period reactivity

Means and standard errors of all cardiovascular reactivity data can be found in Table 2. The 3:1 a priori contrast specified above proved to be reliable for PEP reactivity, F(1, 62) = 9.83, p < .01,  $\eta^2_p = .14$ . Thus, confirming our main hypothesis, PEP reactivity of nondysphoric participants expecting a social reward for good task performance was higher than PEP reactivity of participants in the other three cells (see Figure 1). Moreover, post-hoc cell comparisons using Tukey's HSD procedure indicated significant differences between the nondysphoric / social-reward cell and the two no-reward cells (ps < .04). The other cell comparisons did not prove to be reliable (ps > .28). These results demonstrate that nondysphoric participants mobilized more effort when expecting the possibility to subscribe to the internet site than dysphoric and nondysphoric participants without this possibility. In contrast, dysphoric participants' effort mobilization was not significantly influenced by the presence of the social reward.

# 3.3 Blood pressure reactivity

Similar to PEP reactivity, the a priori contrast for SBP reactivity was significant, F(1, 62) = 8.87, p < .01,  $\eta^2_p = .13$ . The pattern of results for this secondary dependent measure of effort mobilization mirrored PEP reactivity, with nondysphoric participants in the social-reward condition showing the highest SBP reactivity (see Figure 2). Furthermore, post-hoc cell comparisons indicated a significant difference between the nondysphoric / social-reward cell and the dysphoric / no-reward cell (p = .01) as well as a marginally significant difference between the nondysphoric / no-reward cell (p = .10). All other cell comparisons did not prove to be reliable (ps > .28). In contrast to SBP reactivity, the a priori contrast for DBP reactivity was not significant, F(1, 62) = 0.02, p = .88.

# 3.4 Heart rate reactivity

Results for HR reactivity revealed a significant a priori contrast, F(1, 62) = 10.39, p < .01,  $\eta^2_p = .14$ . As can be seen in Figure 3, HR reactivity was highest in the nondysphoric / social-reward cell, compared to the other three cells, thereby paralleling results for PEP and SBP reactivity. Moreover, post-hoc cell comparisons indicated significant differences between the nondysphoric / social-reward cell and the two no-reward cells (ps < .05). None of the other cell comparisons proved to be reliable (ps > .25).

## 3.5 Self-report

Means and standard errors of self-reported success importance and motivation are presented in Table 3. As expected, mean success importance was highest in the nondysphoric / social-reward cell. However, the 3:1 a priori contrast was not significant, F(1, 62) = 2.28, p = .14. Finally, even though self-reported motivation in the reward condition was slightly higher for nondysphoric than for dysphoric participants, this difference was not reliable, t(26.38) = 1.08, p = .29 (degrees of freedom are adjusted due to heterogeneous variances).

#### 3.6 Task performance

Means and standard errors of the two performance indices are displayed in Table 4. Results of a 2 (dysphoria) x 2 (reward) ANOVA revealed no significant main or interaction effects for the number of correct responses, F(1, 62)s < 1.48, ps > .23. Concerning overall reaction times, results revealed a marginally significant main effect of dysphoria, F(1, 62) = 3.21, p = .08, in absence of other main or interaction effects, F(1, 62)s < 1, ps > .51.

# 4. Discussion

The aim of the present study was to test effort-related cardiovascular responses of dysphoric and nondysphoric individuals during the anticipation of a social reward. Research about social rewards in clinical and subclinical depression is extremely sparse, especially for the anticipatory phase and for measures other than central physiological measures. The results of the present study confirm our primary hypothesis stating that effort mobilization—as evidenced by PEP reactivity—would be highest for nondysphoric participants who expected a social reward after successful task performance, compared to the other three cells. Still in line with predictions, dysphoric participants' PEP reactivity was low and unaffected by the presence or absence of the social reward. As suggested by Forbes (2009) and Forbes and Dahl (2012), social reward function was indeed impaired in subclinically depressed individuals, leading to weaker effort mobilization during goal pursuit.

The results of the present study conceptually replicate and extend previous findings by Brinkmann et al. (2014) in several important ways. First, in the previous study, conclusions relied on SBP reactivity as a measure of beta-adrenergic sympathetic impact on the heart. Results of the present study converge with the previous findings in that PEP, SBP, and HR reactivity demonstrate the expected pattern. Second, we modified the experimental procedure and manipulation in several ways to enhance the generalizability of the findings: Participants in the present study were students with various majors in contrast to psychology students in the previous study. Furthermore, we used another type of cognitive task (a mental arithmetic task in contrast to a recognition memory task). Finally, we applied another—potentially more active—kind of social reward by proposing subscription to an internet site that allowed for exchange of information with other successful students, in contrast to entering one's name in the public "best list" in the previous study. Taking both studies together, results confirm the hypothesis of impaired social-reward function in depression (Forbes, 2009; Forbes and Dahl, 2012) and complement the sparse literature about altered neural responses during social reward consumption (Davey et al., 2011; Healey et al., 2014; Olino et al., 2015) and about impaired reward-learning during social reward anticipation (Pechtel et al., 2013).

Results of self-reported success importance and motivation did not reveal the expected group differences. For the interpretation of these findings, several aspects have to be considered: First, even if not reliable, the descriptive patterns indicated higher success importance and motivation ratings in the nondysphoric / social-reward cell, as predicted. Second, self-report measures are subject to self-presentation tendencies (Pyszczynski and Greenberg, 1983; Rhodewalt and Fairfield, 1991). It is thus conceivable that participants were reluctant to admit their true subjective experience. Some of our past studies showed blunted self-reported motivation of depressed individuals (Franzen and Brinkmann, 2016b; Franzen et al., 2016), but not all studies revealed this pattern (Brinkmann and Franzen, 2013; Brinkmann et al., 2014). In the present study, the pattern of motivation ratings together with the clear cardiovascular reactivity pattern make it very likely that dysphoric participants perceived the social reward as less attractive, leading to reduced effort mobilization.

Supplemental exploratory analyses revealed that task performance outcomes (i.e., number of correct responses and overall reaction times) were not significantly influenced by dysphoria or by the reward manipulation. In this context, it is of note that effort mobilization and performance measures can, but do not necessarily have to be positively associated because performance is not only determined by effort but also by task-related ability and chosen strategies (Locke and Latham, 1990). Moreover, task performance can only reflect the effectiveness of behavior but not its efficiency (Eysenck et al., 2007), and effort can have a compensatory function to maintain performance (Hockey, 1997). Therefore, effects on effort mobilization without accompanying effects on performance measures are quite possible.

#### 4.1 Interpretation of cardiovascular response patterns

For the interpretation of PEP reactivity as a measure of sympathetic impact on the heart and therefore as an indicator of effort mobilization, a couple of conditions must be met. It is important to note that PEP reactivity is not only determined by sympathetic influence on the myocardium, but also by cardiac preload and cardiac afterload. Left ventricular filling is one of the most important determinants of preload, while aortic diastolic pressure is one determinant of afterload (Sherwood et al., 1990). Therefore, PEP reactivity should be evaluated only in light of changes in HR and DBP, with changes in HR indicating changes in preload and changes in DBP indicating changes in afterload. In particular, if PEP changes were due to a change in afterload, one would expect that a shortening of the PEP would be accompanied by a decrease of DBP. In a similar vein, if PEP changes were due to a change in ventricular filling, one would expect that a shortening of the PEP would be accompanied by a decrease of DBP. In a similar vein, if PEP changes were due to a change in ventricular filling, one would expect that a shortening of the PEP would be accompanied by a decrease of HR (Obrist et al., 1987; Sherwood et al., 1990). Descriptive data show that the pronounced shortening of PEP in the nondysphoric / social-reward cell is accompanied by an increase of HR and DBP. Therefore, it is unlikely that changes in PEP are caused by changes in aortic diastolic pressure or ventricular filling.

With respect to the reactivity of HR and DBP, it is of note that HR reactivity mirrored the patterns of PEP and SBP reactivity. As noted above, HR is determined by both sympathetic and parasympathetic influences. Therefore, it can display the hypothesized pattern of sympathetic activation but only to the extent that sympathetic activation is not masked by parallel increases in parasympathetic activity and that an increase in HR is not caused by a withdrawal of vagal restraint (Berntson et al., 1993; Brownley et al., 2000; Levick, 2003; Papillo and Shapiro, 1990). The present study is thus in line with several previous studies finding similar effects on PEP and HR in increase (e.g., Brinkmann and Franzen, 2013; Franzen and Brinkmann, 2015; Freydefont and Gendolla, 2012). In contrast to HR reactivity, DBP reactivity did not mirror the patterns of PEP and SBP reactivity. As noted above, DBP strongly depends on vascular resistance and therefore does not qualify as a reliable indicator of beta-adrenergic sympathetic activation. In line with these physiological considerations, evidence for DBP effects in the research on motivational intensity theory has been mixed (Gendolla, Brinkmann, et al., 2012; Gendolla, Wright, et al., 2012).

# 4.2 Responsiveness to social punishment in depression

Together with the studies on neural responses to social reward consumption (Davey et al., 2011; Healey et al., 2014; Olino et al., 2015) and on behavioral response during social reward anticipation (Pechtel et al., 2013), the present study suggests that social rewards might not be as rewarding for depressed individuals as they are for nondepressed individuals, leading to reduced effort mobilization, reduced reward-learning, and altered neural responses. This conclusion raises the question about depressed individuals' responsiveness to negative social consequences, that is, social punishment. In contrast to the relatively clear evidence for

reduced responsiveness to monetary rewards in depression, the literature on the effects of monetary punishment (i.e., losses) in depression is less clear (for a review see Eshel and Roiser, 2010). Whereas some studies show reduced punishment responsiveness in clinical and subclinical depression during anticipation (Gotlib et al., 2010; Schiller et al., 2013), other studies find no differences (Knutson et al., 2008; Olino et al., 2011). Recently, we have argued that these inconsistent results might partly be due to a lack of dissociation of anticipatory and consummatory phases and to a mixture of subjective experiences and objective physiological responses (Franzen and Brinkmann, 2016b).

Regarding the question of social punishment, there is some evidence that social rejection by peers in an online interaction task is quite salient and potentially more painful for depressed adolescents than healthy youth (Silk et al., 2014). Using a similar chatroom interaction task, Stone et al. (2016) show that depressed adolescents with higher trait rumination scores have greater initial pupil dilation during peer rejection than depressed adolescents with lower trait rumination scores. These two studies seem to suggest that the receipt (i.e., the consumption) of peer rejection as a form of social punishment leads to enhanced responsiveness in depression. However, it is of note that both studies diverge from the reward studies described above, in view of the fact that peer acceptance trials (i.e., social reward) did not lead to group differences in reward-related brain regions (Silk et al., 2014) and that increased initial pupil dilation was related to high trait rumination during both rejection and acceptance trials (Stone et al., 2016). It is thus important for future research not only to contrast monetary versus social consequences but also to investigate in more detail different forms of social consequences (e.g., social approval / disapproval, social exchange, social acceptance / rejection, etc.) during both anticipation and consumption, in order to fully understand reward and punishment function in depression.

#### 4.3 Limitations and conclusions

The present study is not without limitations. First, our study is based on subclinical participants with high self-reported depression scores. Previous research on reward responsiveness has frequently found similar results in clinical and subclinical samples (e.g., Liu et al., 2011), including studies on effort-related cardiovascular response (Franzen and Brinkmann, 2016b; Franzen et al., 2016). Therefore, we are confident that the present findings can be generalized to clinically depressed patients. Nevertheless, future research needs to expand the present results to clinical samples. Second, the study design is cross-sectional, assessing self-reported subclinical depression and effort-related cardiovascular responses at the same time. It is therefore not possible to conclude whether reduced effort mobilization

during social reward anticipation is an antecedent, a correlate, or a consequence of high depression scores. It is possible to conceive of a vicious cycle where impaired social reward responsiveness leads to even less social reinforcement from the environment and to even higher depression, and vice versa (Beck et al., 1979). Studies on remitted depressed patients and on high-risk populations suggest that reduced reward responsiveness might have trait-like character (Gotlib et al., 2010; McCabe et al., 2009; McCabe et al., 2012). Nevertheless, future studies using prospective longitudinal designs are needed to answer these questions. Third, the social exchange internet site in the present study was described as a possibility to get information about upcoming experiments and to exchange with other successful participants. Even though the emphasis was put on the social exchange aspect, and informal information confirmed the attractiveness of social exchange as a social reward, we cannot exclude that some participants were similarly attracted by the informational aspect. Future studies might refine the reward description to achieve purely social rewards.

Despite these limitations, the present study has some notable strengths. Based on the theoretical framework of motivational intensity theory (Brehm and Self, 1989) and an established cardiovascular measure of effort mobilization (Kelsey, 2012; Wright, 1996), the present study investigates responsiveness of dysphoric and nondysphoric individuals during the anticipatory, motivational phase of social reward processing. It conceptually replicates and extends the findings by Brinkmann et al. (2014) and complements the relatively sparse literature on neural responses during social reward consumption and behavioral response during social reward anticipation. Results of the present study reveal that subclinically depressed individuals mobilize less effort—in terms of cardiovascular response—to obtain a social reward in form of the possibility to get access to a social exchange internet site. These findings confirm the predictions by Forbes and Dahl (2012) about impaired responsiveness to social forms of reward in depression.

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# Footnotes

<sup>1</sup> Inadvertently, all CES-D raw data assessed online during the questionnaire session were automatically deleted after study completion and could not be retrieved. Therefore, no data are available for calculating Cronbach's  $\alpha$  for the questionnaire session and the correlation between CES-D time 1 and time 2 assessments. However, past studies with similar paradigms have shown high internal consistency (Cronbach's  $\alpha > .92$ ) and high correlations (*r*s > .72) between assessment times (see Brinkmann and Franzen, 2013; Brinkmann et al., 2014).

Means and standard errors of cardiovascular baseline values.

|     |               | М      |        |       | SE    |      |      |      |      |
|-----|---------------|--------|--------|-------|-------|------|------|------|------|
|     |               | PEP    | SBP    | DBP   | HR    | PEP  | SBP  | DBP  | HR   |
| Noi | ndysphoric    |        |        |       |       |      |      |      |      |
|     | No reward     | 95.47  | 105.25 | 56.78 | 67.75 | 3.22 | 2.20 | 1.76 | 3.35 |
|     | Internet site | 103.76 | 106.03 | 60.56 | 80.19 | 2.85 | 2.72 | 1.83 | 2.53 |
| Dys | sphoric       |        |        |       |       |      |      |      |      |
|     | No reward     | 104.52 | 101.88 | 57.47 | 72.34 | 3.83 | 2.16 | 1.20 | 2.16 |
|     | Internet site | 100.06 | 103.98 | 59.44 | 73.39 | 2.75 | 1.99 | 1.02 | 2.70 |

Note. PEP is indicated in milliseconds, SBP and DBP are indicated in millimeters of mercury, and HR is indicated in beats per minute.

Means and standard errors of cardiovascular reactivity.

|     |               | М     |      |      | SE   |      |      |      |      |
|-----|---------------|-------|------|------|------|------|------|------|------|
|     |               | PEP   | SBP  | DBP  | HR   | PEP  | SBP  | DBP  | HR   |
| Non | dysphoric     |       |      |      |      |      |      |      |      |
|     | No reward     | -1.34 | 3.55 | 2.43 | 1.54 | 0.81 | 0.97 | 0.84 | 0.81 |
|     | Internet site | -5.99 | 6.63 | 2.90 | 5.62 | 1.81 | 1.16 | 0.69 | 1.54 |
| Dys | phoric        |       |      |      |      |      |      |      |      |
|     | No reward     | -0.72 | 2.47 | 2.07 | 0.58 | 0.66 | 0.64 | 0.67 | 0.92 |
|     | Internet site | -2.97 | 4.28 | 4.59 | 2.82 | 1.09 | 0.87 | 0.88 | 0.74 |

Note. PEP is indicated in milliseconds, SBP and DBP are indicated in millimeters of mercury, and HR is indicated in beats per minute.

Means and standard errors of self-reported success importance and motivation.

|               | М                  |            | SE                 |            |  |
|---------------|--------------------|------------|--------------------|------------|--|
|               | Success importance | Motivation | Success importance | Motivation |  |
| Nondysphoric  |                    |            |                    |            |  |
| No reward     | 5.97               |            | 0.14               |            |  |
| Internet site | 6.29               | 91.06      | 0.15               | 2.54       |  |
| Dysphoric     |                    |            |                    |            |  |
| No reward     | 5.79               |            | 0.34               |            |  |
| Internet site | 5.91               | 86.13      | 0.23               | 3.81       |  |
|               |                    |            |                    |            |  |

Note. Success importance ratings range from 1 to 7. Motivation ratings range from 0 to 100.

Means and standard errors of correct responses and reaction times.

|               | М                 |                | SE                |                |  |
|---------------|-------------------|----------------|-------------------|----------------|--|
|               | Correct responses | Reaction times | Correct responses | Reaction times |  |
| Nondysphoric  |                   |                |                   |                |  |
| No reward     | 31.50             | 1359.61        | 0.93              | 63.11          |  |
| Internet site | 32.18             | 1270.70        | 0.90              | 61.02          |  |
| Dysphoric     |                   |                |                   |                |  |
| No reward     | 33.41             | 1193.19        | 0.85              | 66.41          |  |
| Internet site | 32.50             | 1192.67        | 1.01              | 81.51          |  |
|               |                   |                |                   |                |  |

Note. Number of correct responses from the 40 equations of the mental arithmetic task. Overall reaction times in milliseconds to all equations.

# **Figure Captions**

Figure 1. Means and standard errors of pre-ejection period reactivity in milliseconds.

**Figure 2.** Means and standard errors of systolic blood pressure reactivity in millimeters of mercury.

Figure 3. Means and standard errors of heart rate reactivity in beats per minute.

# Figure 1





Figure 3

