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Hemodynamic Profiles of Functional and Dysfunctional forms of Repetitive Thinking

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Abstract

Background The ability of the human brain to escape the here and now (mind wandering) can take functional (problem solving) and dysfunctional (perseverative cognition) routes. Although it has been proposed that only the latter may act as a mediator of the relationship between stress and cardiovascular disease, both functional and dysfunctional forms of repetitive thinking have been associated with blood pressure (BP) reactivity of the same magnitude. However, a similar BP reactivity may be caused by different physiological determinants, which may differ in their risk for cardiovascular pathology. ***Purpose*** To examine the way (hemodynamic profile) and the extent (compensation deficit) to which total peripheral resistance and cardiac output compensate for each other in determining BP reactivity during functional and dysfunctional types of repetitive thinking. ***Methods*** Fifty-six healthy participants randomly underwent a perseverative cognition, a mind wandering, and a problem solving induction, each followed by a 5-min recovery period while their cardiovascular parameters were continuously monitored. ***Results*** Perseverative cognition and problem solving (but not mind wandering) elicited BP increases of similar magnitude. However, perseverative cognition was characterized by a more vascular (versus myocardial) profile compared to mind wandering and problem solving. As a consequence, BP recovery was impaired after perseverative cognition compared to the other two conditions. ***Conclusions*** Given that high vascular resistance and delayed recovery are the hallmarks of hypertension the results suggest a potential mechanism through which perseverative cognition may act as a mediator in the relationship between stress and risk for developing precursors to cardiovascular disease.

Keywords Perseverative Cognition; Mind Wandering; Problem Solving; Hemodynamic Profile; Cardiac Output; Total Peripheral Resistance

People spend a large part of their time engaging in mind wandering, which often leads to going over the same thoughts again and again, called repetitive thinking. Such an extremely common cognitive process can take functional (problem solving) and dysfunctional (rumination, worry) routes [1]. The Perseverative Cognition Hypothesis specifically suggests that rumination about the past and worrisome thoughts about the future (i.e., perseverative cognition) cause a "fight-or-flight" action tendency, followed by a cascade of biological events such as increases in cardiovascular activity and this persistent physiological activation may have an impact on an individual's health ultimately leading to somatic disease [2, 3]. A recent meta-analysis supported this view, providing evidence of increased cardiovascular, autonomic, and endocrine nervous system activity associated with rumination and worry [4].

However, previous studies repeatedly showed that even ostensibly more functional forms of repetitive thinking, such as mind wandering and problem solving could be associated with increased physiological activity. For example, Verkuil and colleagues [5] found cardiac effects of the same magnitude during worrying and problem solving, leading the authors to conclude that "mere mental load may be responsible for at least a part of the physiological effects of worry" (page 448). Similarly, several studies linked mind wandering per se with increased physiological activation [6-8].

If both functional and dysfunctional forms of repetitive thinking were associated with physiological activity, why would only the latter be associated with increased risk for somatic disease? In terms of cardiovascular activity, it has to be noted that elevations in blood pressure (BP) of the same magnitude can be elicited by different patterns of compensatory changes in cardiac output and total peripheral resistance [9]. Therefore, looking at the physiological determinants of BP becomes more informative than focusing on BP responses per se [10]. The term ''hemodynamic profile'' describes the relationship between cardiac output and total peripheral resistance in the homeostatic regulation of BP [11]. The first aim of the present study was to examine the hemodynamic profiles of functional and dysfunctional forms of repetitive thinking.

We hypothesized that perseverative cognition would be characterized by a predominantly vascular hemodynamic profile whereas problem solving and mind wandering would have a more myocardial or mixed profile. If this were true, then the cardiovascular reactivity of the same magnitude that has been shown to characterize perseverative cognition and problem solving would be associated with distinctive hemodynamic patterns, with different implications for health. In fact elevated BP driven by total peripheral resistance, compared to cardiac output, has been linked to increased risk of cardiac events and mortality [9, 12, 13].

The second aim of the present study, closely connected to the first, was to show that another crucial difference between functional and dysfunctional forms of repetitive thinking concerns the duration of the concomitant physiological activation. Indeed only prolonged or chronic activation can lead to the pathogenic state that eventually leads to organic disease [2]. A major consequence of the dominance of reactivity-based theories has been the failure to examine the duration of activation. This is an important limitation considering that a recent meta-analysis showed that poor recovery from laboratory challenges provided incremental value for predicting adverse cardiovascular outcomes beyond reactivity per se [14]. We hypothesized that functional and dysfunctional forms of repetitive thinking would be characterized by an equivalent BP reactivity but only dysfunctional forms would be associated with delayed BP recovery.

The two hypothesis of the present study are closely interconnected. In terms of hemodynamics, delayed recovery has been primarily associated with vascular responding [15]. For example, Steptoe and Marmot [16] found that an increase in BP over a 3-year period was predicted by impaired post-stress recovery and that the elevation in BP recorded during the recovery period was determined by vascular rather than cardiac responses. Consistent with this idea, extended mental stress seems to be characterized by transient increases in cardiac output but prolonged changes in total peripheral resistance [17]. Thus, if both our hypothesis are confirmed, it is likely that the delayed recovery that characterizes perseverative cognition would actually be due to its "vascular nature".

In light of the role played by anxiety, depression, and anger-in in augmenting cardiovascular risk [18], the present study also examined which of these personality factors, as well as the dispositional tendency to engage in rumination and worry and state levels of sadness and anxiety, better predicted the hemodynamic profile that characterizes perseverative cognition.

To the best of our knowledge, this is the first study to examine the physiological mechanisms underlying the cardiovascular consequences of functional and dysfunctional forms of repetitive thinking and to examine the hemodynamic mechanisms through how this may ultimately lead to cardiovascular disease.

Method

Participants

The sample was composed of university students and employees. Of the 65 subjects who agreed to participate in the study, 9 were excluded due to Portapres device (see 'cardiovascular monitoring' below) malfunction. The final sample was composed of 26 women and 30 men with a mean age 24.5 (3.9) years. All subjects were Caucasian. Exclusionary criteria, assessed during a pre-screening questionnaire, were: diagnosis of psychiatric disorders (current and/or past), diagnosis of hypertension or heart disease, any other disease or use of drugs/medications that might affect cardiovascular function, obesity (body mass index > 32 kg/m^2), menopause, use of oral contraceptives during the previous 6 months, and pregnancy or childbirth within the last 12 months.

Participants were compensated for their time. The protocol was approved by the Bioethical Committee of S. Lucia Foundation, Rome, Italy.

Procedure

Participants were informed of the following restrictions: no caffeine, alcohol, nicotine, or strenuous exercise for 2 h prior to the appointment. After reading and signing the informed consent form, the continuous BP cuff was attached on the middle finger of participants' right hand. After

calibration, the experimental protocol started with a 'vanilla' baseline period [19]. Then, all participants took part in three experimental conditions: a perseverative cognition induction, a mind wandering induction, and a cognitive problem-solving task.

The experimental conditions were presented in counterbalanced order. Each condition lasted 5 minutes and was followed by a 5-minute recovery period. After baseline, each experimental condition, and each recovery period, participants rated their mood and thoughts by a series of visual analogue scales (VAS). Cardiovascular parameters were continuously monitored by the Portapres device throughout the experimental session.

Experimental manipulation instructions

Perseverative cognition induction: "*Now I would like you to recall an episode that happened in the past year that made you feel sad, anxious, or stressed, or something that may happen in the future that worries you. Then, I would like you to think about this episode in detail, for example about its possible causes, consequences, and your feelings about it. Please take as much time as you need to identify the event and press the button whenever you are ready*".

Mind wandering induction: "*Now I would like you to let your mind wander without getting stuck on any particular thought"*.

Problem solving induction: "*Now I would like you to solve a series of syllogisms. Please select "Yes" if you think that the presented syllogism is valid, select "No" otherwise"*. Example: No A are B. Some C are B. Therefore, some C are not A.

Recovery periods: "*The task is terminated. Now I would like you to rest until the instructions for the following task appear on the screen".*

Measures

Cardiovascular Monitoring

Noninvasive continuous measurement of beat-to-beat BP was obtained throughout the study

with the Portapres II (FMS; The Netherlands) device, which has been shown to reliably compare with intra-aortic pressure measurement [20]. The arterial pressure signal was analyzed using BeatScope® software to obtain systolic (SBP) and diastolic BP (DBP), cardiac output, and total peripheral resistance. SBP, DBP, cardiac output, and total peripheral resistance reactivity values were computed by subtracting the initial baseline from task values. SBP, DBP, cardiac output, and total peripheral resistance recovery values were computed by subtracting task values from post-task values. Hemodynamic Profile and Compensation Deficit were computed as detailed in the following section.

Hemodynamic Profile and Compensation Deficit

Hemodynamic profile (HP) and compensation deficit were assessed following the orthogonal, physiologically grounded model proposed by Gregg and colleagues [21]. The model is derived from the multiplicative relationship between cardiac output and total peripheral resistance in determining mean arterial pressure [22] and the computation is based on the following equation:

$$\log(\textit{cardiac output})r + \log(\textit{total peripheral resistance})r = \log(\textit{mean arterial pressure})r$$

where r indicates:

a) a ratio of task to baseline values for reactivity periods [10, 21];

b) a ratio of recovery to task values for recovery periods [15].

This approach has the advantage of not being based on any artificial taxonomy that would ignore the continuous nature of cardiovascular measurements. The outcome is a continuous variable by which participants are described as more vascular (greater HP values) when the algebraic increase in log(*total peripheral resistance*)r exceeds that in log(*cardiac output*)r, and more myocardial when the algebraic increase in log(*cardiac output*)r exceeds that in log(*total peripheral resistance*)r. Compensation deficit (CD) increases as the algebraic sum of the log(*cardiac output*)r and log(*total peripheral resistance*)r values increase [21]. Greater CD values indicate that increased total peripheral resistance is not compensated by a commensurate decrease in

cardiac output.

Visual Analog Scales (VAS)

After baseline, each task and each recovery period, participants were asked to rate their current levels of feeling Anxious, Angry, Happy, Tired, and Sad on separate visual analogue 100-point scales. The same scale was used to inquire about participants' ongoing cognitive activity: "How much for the duration of the task were you": 1) mind wandering, 2) ruminating, 3) worrying. For each VAS, change scores were computed by subtracting the initial baseline from task values for reactivity periods and by subtracting the task from post-task values for recovery periods.

Questionnaires

Ruminative Response Scale is a measure of depressive rumination tendencies assessed by how often people engage in responses to depressed mood that are self-focused (e.g., I think "Why do I react this way?"), symptom-focused (e.g., I think about how hard it is to concentrate), and focused on the possible consequences and causes of one's mood (e.g., I think "I won't be able to do my job if I don't snap out of this") [RRS; 23]. Reliability and validity of the RRS were supported through several longitudinal studies with Cronbach's α ranging from 0.75 to 0.80 [24, 25].

Penn State Worry Questionnaire is a 16-item self-report questionnaire mainly focused on future outcomes (e.g., As soon as I finish one task, I start to worry about everything else I have to do) and commonly used to assess pathological worry in both clinical and non-clinical populations [PSWQ; 26]. The PSWQ has demonstrated good discriminant validity [27-29] and high internal consistency and test–retest reliability with Cronbach's alphas ranging between .86 and .95 [28].

State Trait Anxiety Inventory includes a measure of trait dispositional anxiety that targets how respondents "generally feel" (e.g., I am a steady person) [STAI; 30]. High validity and reliability (Cronbach's alpha from .86 to .95) have been documented [31, 32].

Center for Epidemiologic Studies Depression Scale is a 20-item self-report scale designed to

measure depressive symptomatology (e.g., I felt that everything I did was an effort) over the previous week in the general population [CES-D; 33]. The validity of the CES-D has been repeatedly confirmed, although some specific items are currently a matter of debate [34]. Cronbach's alphas are above .85 in the general population and .90 in depressed patients confirming high reliability [33].

Anger-In subscale of the *Spielberger Trait Anger Expression Inventory* is a measure of the tendency of individuals to hold in or suppress responses to anger provocation (e.g., I control my urge to express my angry feelings) [STAXI; 35]. The STAXI has consistently demonstrated evidence to support its validity and reliability as an instrument to assess anger (overall Cronbach's alpha above .90) [36].

Data Analysis

All data are expressed as means (SD). Differences at $p \leq .05$ were regarded as significant. Data processing was performed with the software modules of SPSS 23 (IBM). SBP, DBP, cardiac output, and total peripheral resistance reactivity and recovery, hemodynamic profile, compensation deficit, and scores on personality questionnaires were treated as continuous variables.

Sex differences were analyzed by *t*-tests and χ^2 tests.

To test for differences in reactivity and recovery levels for the three experimental conditions, a series of 3 (Induction: Perseverative Cognition, Mind Wandering, Problem Solving) x 2 (Time: Reactivity, Recovery) x 6 (Order) General Linear Models (GLMs) were performed on SBP, DBP, cardiac output, total peripheral resistance, and each VAS. Reactivity and recovery change scores were used in these GLMs.

Consistent with the approach adopted by James and Gregg [37], one-sample t tests were used to test the difference from zero of hemodynamic profile and compensation deficit scores for each condition and subsequent recovery periods. A significant *t*-test result for hemodynamic profile was taken to indicate either a vascular (positive *t* value) or a myocardial profile (negative *t* value). A

nonsignificant hemodynamic profile result coupled with a significant compensation deficit result means that the response was mixed (i.e., neither vascular nor myocardial). No hemodynamic response at all was deemed to have occurred when both hemodynamic profile and compensation deficit were not significant.

To examine the predictive power of both state moods and dispositional traits in determining the hemodynamic profile that characterizes functional and dysfunctional forms of repetitive thinking above and beyond traditional predictors, three hierarchical multiple regression analyses were conducted with sex entered in the first stage (see below); mood and thought changes (anxious, sad, ruminating, worrying) during the corresponding induction entered in the second stage, and the questionnaires scores entered in the third stage as the independent variables. Hemodynamic profile during the perseverative cognition, mind wandering, and problem solving inductions served as dependent variables.

Results

Descriptive statistics

Significant sex differences emerged for baseline DBP (t (54) = 2.18; p = .03), and scores on the CESD (t (54) = 2.91; p = .01), STAI (t (54) = 3.12; p = .003), PSWQ (t (54) = 2.65; p = .01), and RRS (t (54) = 2.17; p = .04). As shown in Table 1, men were characterized by higher levels of DBP and trait worry, whereas women had higher tendencies toward anxiety, depression, and depressive rumination, therefore sex was included as a covariate in all the analyses concerning these variables.

Blood Pressure, Total Peripheral Resistance, and Cardiac Output Reactivity and Recovery

The GLM having SBP as the dependent variable yielded significant effects of Time, F(1,50) = 10.19, p = .002; η^2 = .17, Induction F(2,100) = 7.82, p = .001; η^2 = .14, and Time x Induction interaction, F(2,100) = 6.20, p = .003; η^2 = .11. As depicted in Figure 1, post hoc comparisons showed that SBP increases were significantly larger during perseverative cognition and problem

solving compared to mind wandering (*ps* < .002). Moreover, SBP significantly decreased from problem solving to recovery from the same task ($p < .0001$), but not for mind wandering, and marginally increased from perseverative cognition to the subsequent recovery period ($p = .07$). Within the recovery period, SBP was higher during perseverative cognition compared to mind wandering and problem solving (*ps* < .002), with no significant differences between the last two conditions.

As for DBP, significant effects of Time, $F(1,50) = 7.37$, $p = .01$; $\eta^2 = .13$, Induction $F(2,100) = 3.83$, $p = .02$; $\eta^2 = .07$, and Time x Induction interaction, $F(2,100) = 5.59$, $p = .005$; $\eta^2 = .10$ emerged. As illustrated in Figure 1, during both perseverative cognition and problem solving there were significantly larger DBP increases compared to mind wandering (*ps* < .01). Moreover, DBP significantly decreased from problem solving to recovery from the same task ($p = .01$), but this was not the case for mind wandering and perseverative cognition. Within the recovery period, DBP was higher during perseverative cognition compared to mind wandering and problem solving (*ps* < .01), with no significant differences between the last two conditions.

The GLM having cardiac output as the dependent variable yielded a marginally significant effect of Induction, $F(2,100) = 2.68$, $p = .07$; $\eta^2 = .05$ with larger increases in cardiac output during problem solving compared to perseverative cognition and mind wandering (*ps* < .02) and during mind wandering compared to perseverative cognition ($p = .08$).

As for total peripheral resistance, significant effects of Time, $F(1,50) = 5.97$, $p = .02$; $\eta^2 = .11$, Induction $F(2,100) = 26.53$, $p < .0001$; $\eta^2 = .35$, and Time x Induction interaction, $F(2,100) = 3.93$, $p = .02$; $\eta^2 = .07$ emerged. Post hoc comparisons showed that total peripheral resistance increased more during perseverative cognition compared to mind wandering and problem solving (*ps* < .0001) with no differences between the last two conditions. A marginally significant result emerged for the recovery phase, with higher total peripheral resistance after perseverative cognition compared to the other two inductions ($p = .068$).

Hemodynamic Profile and Compensation Deficit

Figure 2 shows the relationship between hemodynamic profile and compensation deficit scores for the different tasks. No significant sex differences emerged in the hemodynamic profile induced by the different experimental conditions. One-sample *t*-tests for hemodynamic profile and compensation deficit indicated that a vascular profile was produced by the perseverative cognition induction, $t(55) = 3.85$, $p < .0001$, whereas the problem-solving condition evoked a myocardial profile, $t(55) = -3.35$, $p < .0001$, and no hemodynamic response occurred during the mind wandering induction, $t(55) = 0.02$, $p = .98$. A significant compensation deficit emerged during both the perseverative cognition ($t(55) = 6.64$, $p < .0001$), and the problem solving ($t(55) = 5.86$, $p < .0001$) -but not during the mind wandering- inductions providing a potential explanation for the increase in BP that characterized these two tasks.

When recovery after the perseverative cognition induction was examined, no hemodynamic response seemed to occur in the transition from reactivity to recovery ($t(55) = -0.42$, $p = .68$ and $t(55) = 0.57$, $p = .57$ for hemodynamic profile and compensation deficit, respectively), indicating that the vascular profile provoked by the induction did not change during the subsequent recovery period. A mixed profile characterized the transition from reactivity to recovery periods for both mind wandering ($t(55) = 0.06$, $p = .96$ and $t(55) = 2.90$, $p = .005$ for hemodynamic profile and compensation deficit, respectively) and problem solving ($t(55) = 1.03$, $p = .31$ and $t(55) = 3.14$, $p = .003$ for hemodynamic profile and compensation deficit, respectively).

VAS

To control for violations of sphericity degrees of freedom were corrected using Greenhouse-Geisser estimates of epsilon.

As shown in Figure 3 and Table 2, self-reported levels of mind wandering, rumination, and worry confirmed effectiveness of the experimental manipulations. For the GLM having Mind wandering as the dependent variable, main effects of Time, $F(1,50) = 29.08$, $p < .0001$, $\eta^2 = .37$,

and Induction $F(2,100) = 7.57$, $p = .005$, epsilon = .60, $\eta^2 = .13$, were qualified by an interaction between Time and Induction, $F(2,100) = 21.71$, $p < .0001$, epsilon = .82, $\eta^2 = .30$. A significant main effect of Task Order, $F(5,50) = 3.19$, $p = .01$, $\eta^2 = .24$ and a Task Order x Induction interaction, $F(10,100) = 3.25$, $p = .001$, $\eta^2 = .25$ also emerged. As to Rumination, significant main effects of Time, $F(1,50) = 14.65$, $p < .0001$, $\eta^2 = .23$, and Induction, $F(2,100) = 89$, $p < .0001$, epsilon = .54, $\eta^2 = .64$, and Time x Induction interaction ($F(2,100) = 84.51$, $p < .0001$, epsilon = .74, $\eta^2 = .63$) emerged. For Worry, the GLM yielded a main effect of Induction, $F(2,100) = 26.31$, $p < .0001$, epsilon = .55, $\eta^2 = .35$ and a significant Time x Induction interaction, $F(2,100) = 46.83$, $p < .0001$, epsilon = .77, $\eta^2 = .48$. Figure 3 illustrates significant post hoc comparisons.

As to self-reported mood (see Table 2 for means and standard deviations and Figure 3 for significant post-hoc results), the GLM having Angry as a dependent variable revealed main effects of Time, $F(1,50) = 25.32$, $p < .0001$, $\eta^2 = .34$, and Induction $F(2,100) = 42.52$, $p < .0001$, epsilon = .54, $\eta^2 = .46$, qualified by an interaction between Time and Induction, $F(2,100) = 25.52$, $p < .0001$, epsilon = .76, $\eta^2 = .34$.

For Anxious, a significant effect of Induction, $F(2,100) = 5.46$, $p = .01$, epsilon = .55, $\eta^2 = .10$, and a Time x Induction interaction, $F(2,100) = 14.11$, $p < .0001$, epsilon = .81, $\eta^2 = .22$ emerged, with higher increases during perseverative cognition compared to the other two inductions.

No significant effects emerged for Tired.

The GLM having Happy as a dependent variable revealed main effects of Time, $F(1,50) = 12.28$, $p = .001$, $\eta^2 = .20$, and Induction $F(2,100) = 14.60$, $p < .0001$, epsilon = .55, $\eta^2 = .23$, qualified by an interaction between Time and Induction, $F(2,100) = 4.80$, $p = .01$, epsilon = .79, $\eta^2 = .09$.

As to Sad, the GLM revealed main effects of Time, $F(1,50) = 6.98$, $p = .01$, $\eta^2 = .12$, Induction $F(2,100) = 26.25$, $p < .0001$, epsilon = .60, $\eta^2 = .34$, and Time x Induction interaction, $F(2,100) = 21.92$, $p < .0001$, epsilon = .73, $\eta^2 = .31$.

Overall, participants reported to be angrier, sadder, and more anxious during the perseverative

cognition induction compared to the mind wandering and problem solving inductions.

Hierarchical Regression

Given the high correlation between RRS and CESD scores (r = .81; p < .0001) and between PSWQ and STAI (r = .77; p < .0001) scores, only STAI, CESD, and STAXI-In were included as predictors, to prevent multicollinearity. For the same reason, only Sad and Anxious (correlations with Rumination: r = .31; p = .02 and r = .50; p < .0001, respectively) were included in the models.

Results from the hierarchical regression for the prediction of hemodynamic profile during perseverative cognition did not reveal a significant relationship between sex and the dependent variable (β = .08; p = .65; R^2 = .006). Momentary mood changes significantly added to the prediction with a higher anxiety response to the perseverative cognition induction being a significant predictor of a more vascular profile during perseverative cognition (β = .41; p = .04; R^2 = .10). Dispositional traits further added to the prediction of hemodynamic profile during perseverative cognition, particularly with higher Anger-In scores being associated with a more vascular profile during perseverative cognition, β = .35; p = .04; R^2 = .28.

Neither Sex (β = -.05; p = .77; R^2 = .01), nor momentary mood changes (Sad, β = -.13; p = .47; Anxious, β = .08; p = .67; R^2 = .02) were significant predictors of hemodynamic profile during problem solving. Among dispositional traits, higher Anger-In scores significantly predicted a more vascular profile during problem solving, β = .38; p = .04; R^2 = .16.

Neither Sex (β = .15; p = .35; R^2 = .02), nor momentary mood changes (Sad, β = .04; p = .84; Anxious, β = -.02; p = .93; R^2 = .02), nor dispositional traits, (STAI, β = .21; p = .50; CES-D, β = .05; p = .87; STAXI-In, β = .08; p = .65; R^2 = .06) were significantly associated with hemodynamic profile during mind wandering.

Results did not change when the analyses were performed replacing STAI and CES-D with PSQW and RRS, with these two variables not being significant predictors in any of the examined hierarchical regression models. Similar results were also obtained if Anxious and Sad were

replaced by Rumination and Worry, with higher levels of Rumination predicting a more vascular profile during the perseverative cognition (β = .45; p = .01; R^2 = .11) and the problem solving induction (β = .31; p = .03; R^2 = .07). Worry did not significantly add to the predictions (see the Limitation section for a possible explanation).

The absence of excessive multicollinearity was suggested by variance inflating factors not substantially greater than one and tolerance well above 0.2.

Discussion

The present findings supported our hypotheses showing that perseverative cognition was associated with the same BP reactivity as more functional forms of repetitive thinking, but was uniquely characterized by a more vascular hemodynamic profile and (subsequently) delayed recovery.

Previous studies similarly showed that problem solving and worry elicited a cardiovascular reactivity of the same magnitude [5]. The present investigation extended such results with the inclusion of mind wandering as a comparison condition. Some authors previously reported an association between episodes of mind wandering and increases in heart rate, skin conductance [6, 7], and enhancement of the blink reflex [8]. However, when mind wandering was directly compared to or differentiated from perseverative cognition, its association with physiological reactivity disappeared both in laboratory [38] and in ambulatory studies [39-41]. These findings are underscored by the lower BP responses during the mind wandering induction in the current study.

Furthermore, we examined the hemodynamic correlates of functional and dysfunctional forms of repetitive thinking. Even if that was not the main objective of a previous study, the hemodynamic profile of angry rumination in comparison with a series of stressful tasks including a logical-mathematical task (which can be viewed as a form of problem solving) has been reported [10]. These findings are in line with our current results, in the way that the authors report a more vascular profile during rumination and a mixed profile during the logical-mathematical task. Here, we

consistently found a vascular profile during perseverative cognition and a more myocardial profile during problem solving, as well as a mixed profile during mind wandering.

The present findings are in line with the Obrist's distinction of active versus passive coping [42]. In the Obrist view, active coping, which refers to an individual's attempts to exert personal control over environmental events, leads to significant beta-adrenergic influence on myocardial responses. However, such beta-adrenergic reactions become attenuated in situations that offer little opportunity to exercise instrumental control (i.e., passive coping), in which a significant vascular response is instead elicited. Problem solving can be considered as an example of active coping whereas perseverative cognition can be representative of passive coping. In our opinion, due to the nature of our tasks, it is possible to exclude that our results are due to quantitative differences in mental effort [5]. In terms of mental engagement, problem solving may be viewed as the most effortful condition but mind wandering (the default mode of operation of our brain) would be the least effortful or equal to perseverative cognition, making it difficult to interpret the present cardiovascular differences between these two experimental conditions solely in terms of mental effort. As a limit, this argument has not been demonstrated in this study in any empirical manner.

Drawing on Obrist's theory [42], Blascovich developed the biopsychosocial model of challenge and threat, according to which perceived challenge versus perceived threat reliably result in distinct patterns of physiological changes [43]. In this model, challenge is characterized by higher cardiac output and lower total peripheral resistance (a pattern similar to that taking place during aerobic exercise), whereas threat is characterized by the opposite pattern (i.e., higher total peripheral resistance and lower cardiac output). This view nicely fits with our finding of higher state anxiety being a significant predictor of a more vascular profile during perseverative cognition. In the Blascovich view, the threat cardiovascular pattern, which is characterized by arterial constriction rather than dilation, can result in strain on the coronary arteries, leading to damage, scarring, plaque deposits, and eventually ischemic heart disease or, if prolonged or repeated over time, hypertension. Indeed persistent or excessive vasoconstriction is a pathognomonic indicator of hypertension [9, 12,

13].

Keeping in mind the limitation that a 5-minute recovery period may not have been adequate in length [16], the second core result of the present study suggests that another crucial difference between functional and dysfunctional forms of repetitive thinking relies on the duration of the concomitant physiological activation. Perseverative cognition was in fact not only characterized by an increase in BP during the induction itself but also by a lack of BP recovery at the end of the task. Such sustained cardiovascular activation is not surprising as self-reported levels of rumination and worry during the recovery period suggest that participants were not able to stop perseverative cognition when asked to do so. This is of particular interest in light of evidence that hypertension is characterized by both elevated total peripheral resistance and delayed recovery [9, 44, 45]. It has further been suggested that recovery impairments may be among the earliest precursors to the development of essential hypertension in normotensive subjects at genetic risk of hypertension [46].

The effects of perseverative cognition on mood are one of the most well-replicated findings in this field [47] and do not need to be further commented.

When we looked at possible associations with dispositional traits, we found that a more vascular hemodynamic profile during perseverative cognition was predicted by higher levels of dispositional anger-in. Delayed recovery following anger provocation has been previously described and specifically linked to rumination [39-41]. More specifically, suppression of anger expression (i.e., anger-in) was specifically related to high BP, atherosclerosis, and delayed recovery [48-52]. A previous study found an association between anger-in levels and baroreceptor sensitivity during anger rumination [53], which is in line with the delayed recovery of BP that was seen in the present study after the perseverative cognition induction. Lastly, a vascular hemodynamic profile during angry rumination has been reported elsewhere [10], enhancing the robustness of the present results.

Some limitations need to be mentioned. First, the sample size was relatively small and may not have been adequate in some of the comparisons. Second, with a recovery period of adequate

duration we might have been able to capture the time needed for BP to fully recover after the perseverative cognition induction. Third, we experimentally induced perseverative cognition, mind wandering, and problem solving in the laboratory, whereas in the real world spontaneity is an intrinsic feature of these cognitive processes. This is particularly true for the mind wandering induction, whose investigation is commonly challenged by the lack of direct experimental control and its covert nature [54]. Among the methods generally used to investigate mind wandering, we preferred retrospective report to experience sampling to avoid the risk of altering the natural dynamics of the experience by periodically disrupting it [54]. A growing body of research employing resting state imaging measures and retrospective reports of mind wandering indicate that -in the absence of tasks requiring deliberative processing- the mind tends to wander [55, 56]. The retrospective report of mind wandering employed at the end of the induction has the advantage to preserve the integrity of time-course data and has been proven to be particularly suited to relate mind wandering to its physiological signatures, as suggested by studies using pupillometry [57] and EEG [58]. Directly related to this point, a further limitation of the present study is that we relied on post-task subjective reports (VAS) as the only measure of effectiveness for our inductions. Replication studies should include more objective measures of the distinct ongoing mental activities, such as EEG and test the possibility that rumination and worry have their own unique hemodynamic signatures. Our exploratory analysis seems to suggest that state rumination is a better predictor of hemodynamic profile than worry. This result should be, however, interpreted with caution especially considering that the Italian meaning of the terms used to measure state rumination and state worry are not exactly the same as in English. In Italian, the distinction between these two words does not exist in daily language; moreover, the word rumination encompasses threat (as confirmed with the significant correlation with state anxiety), whereas worry has a much milder meaning in terms of the evoked emotion compared to English. Lastly, despite the strength of the within-subject design used, and the counterbalancing of the order of the three inductions, and they may still have influenced each other in a non-natural way, each of them either

enhancing or flattening the response to another. Our methodological approach could reduce the strength of the emotion experienced if some emotional episodes are not recalled as reliably and if the emotions are not relived as vividly.

Limitations notwithstanding, the present study is clinically relevant in that it provides further insights into the consequences of perseverative cognition for cardiovascular risk, furnishing information on its hemodynamics compared to more functional forms of repetitive thinking. Obviously, replication with a larger sample size, a wider range of inductions, and a longer recovery period is needed to test the robustness of the present findings.

Table1 Sex differences at baseline

	Women (n = 26)	Men (n = 30)	t/χ^2
Age (years)	24.2 (3.4)	24.7 (4.5)	0.41
BMI (Kg/m^2)	21.9 (2.7)	22.7 (4.1)	0.80
Education	11 L, 14 M, 1 H	13 L, 15 M, 2 H	0.25
SBP (mmHg)	125.7 (23.4)	133.7 (18.3)	1.44
DBP (mmHg)	74.5 (13.2)	81.8 (11.9)	2.18*
CO (L/min)	5.2 (1)	5.7 (1.2)	1.87
TPR ($dyn/cm^2/s$)	1192.3 (231)	1152.4 (149.7)	0.78
Nicotine	16 N, 10 Y	24 N, 6 Y	2.33
RRS	51.5 (13.4)	42.7 (11.1)	2.17*
PSWQ	43.3 (10.3)	54.2 (11.9)	2.65*
STAI	49.1 (10.6)	39.3 (8.9)	3.12*
CES-D	43.3 (10.3)	34.5 (8.6)	2.92*

Note. BMI = Body Mass Index; SBP = Systolic Blood Pressure; DBP = Diastolic Blood Pressure; CO = Cardiac Output; TPR = Total Peripheral Resistance; RRS = Ruminative Response Scale; PSWQ = Penn State Worry Questionnaire; STAI = State Trait Anxiety Inventory; CES-D = Center for Epidemiologic Studies Depression Scale.

* $p < 0.05$

Table 2 Means and standard deviations of VAS scores during the three experimental conditions (reactivity) and subsequent recovery periods

	Perseverative Cognition		Mind Wandering		Problem Solving	
	Reactivity	Recovery	Reactivity	Recovery	Reactivity	Recovery
Ruminating	44.6 (33.4)	41.2 (35.0)	-85.8 (60.4)	-44.6 (33.4)	-7.9 (24.2)	6.9 (27.2)
Worrying	24.2 (35.1)	29.9 (34.5)	-54.1 (62.9)	-24.2 (35.1)	-19.1 (28.4)	16.0 (29.7)
Wandering	-14.2 (36.7)	26.6 (39.3)	40.8 (70.1)	14.2 (36.7)	-9.5 (26.9)	26.8 (35.8)
Happy	-12.6 (21.4)	3.8 (18.9)	16.4 (34.29)	12.6 (21.4)	-6.7 (21.9)	0.5 (15.7)
Sad	20.2 (27.2)	-12.6 (26.3)	-32.8 (47.1)	-20.2 (27.2)	-2.1 (19.7)	1.8 (11.9)
Tired	3.9 (29.3)	4.5 (17.4)	0.6 (38.8)	-3.9 (29.3)	1.1 (19.6)	3.4 (14.9)
Anxious	9.9 (28.2)	-12.5 (23.3)	-22.4 (45.0)	-9.9 (28.2)	-7.2 (23.9)	1.7 (17.1)
Angry	22.0 (25.4)	-13.3 (23.5)	-35.3 (43.6)	-22.0 (25.4)	6.1 (20.3)	0.4 (16.5)

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Figure captions

Figure 1. Systolic and diastolic blood pressure reactivity and recovery for each experimental condition.

Note. Error bars represent standard deviations of the mean. PC = Perseverative Cognition; MW = Mind Wandering; PS = Problem Solving; SBP = Systolic Blood Pressure; DBP = Diastolic Blood Pressure.

Figure 2. Scatterplots for hemodynamic profile and compensation deficit during each task. A ‘‘more vascular’’ profile is associated with more positive values along the hemodynamic profile axis and a ‘‘more myocardial’’ profile is associated with more negative values along the hemodynamic profile axis. A ‘‘higher deficit’’ in compensating is associated with more positive values on the compensation deficit axis and a ‘‘lower deficit’’ in compensating is associated with more negative values on the compensation deficit axis.

Figure 3. VAS reactivity and recovery change scores for perseverative cognition (black), mind wandering (light grey), and problem solving (dark grey).

Note. Error bars represent standard deviations of the mean. * $p < .05$; ** = $p < .0001$. MW = Mind Wandering.