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ORIGINAL ARTICLE

A Network Approach to Understanding the Emotion Regulation Benefits of Aerobic Exercise

Emily E. Bernstein[1] · Alexandre Heeren[2] · Richard J. McNally[1]

Abstract

Regular and even single sessions of aerobic exercise may benefit emotional health. Experiments show that prior exercise hastens emotional recovery following a stressor despite not changing reports of rumination or other emotion regulation difficulties. We use network analyses to explore whether traditional approaches for conceptualizing and measuring rumination (i.e. sum scores) could be occluding exercise-induced changes to emotion regulation. Participants ($n=226$) were randomly assigned to a cycling ($n=113$) or stretching control condition ($n=113$). They then underwent a stressful speech task, followed by a recovery period. State rumination was measured through self-report. Graphical LASSO and relative importance networks and accompanying strength centrality indices were computed. Similar patterns emerged in both models. Declines in the strength centrality of self-criticism in the cycling group stood out. Exercise may alter the relations between rumination processes and target self-criticism in particular. This perspective offers important information about how exercise enhances well-being through emotion regulation as well as how to intervene on emotion regulation deficits more generally.

Keywords Exercise · Rumination · Network analysis · Relative importance · Emotion

Introduction

Years of research and anecdotal observations suggest that regular and even single sessions of aerobic exercise are beneficial for emotional health. For example, exercisers report more positive affect, greater wellbeing, less anxiety, and less depressed mood than do their sedentary peers (Goodwin 2003; Harvey et al. 2010; Ströhle 2009). Engaging in regular physical activity appears to mitigate risk for developing depression and other emotional disorders (Harvey et al. 2017; Ströhle 2009). Experience sampling studies have shown that physical activity weakens the connection between perceived stress and daily reported negative affect (Flueckiger et al. 2016; Puterman et al. 2017). In the laboratory, even single sessions of aerobic exercise can attenuate prolonged physiological and emotional responses to subsequent experimental stressors (Bernstein and McNally 2016, 2017; Mata et al. 2013; Puterman et al. 2011). In other words, exercise seems to help people bounce back. The question remains: how does this happen?

Curiously, experimental studies of acute aerobic exercise have not found changes in reports of difficulty regulating one's emotions following a stressor (Bernstein and McNally 2016, 2017) and primarily physiological changes (e.g. parasympathetic vagal tone) cannot fully account for these emotional benefits (Harvey et al. 2017). In this article, we explore rumination as a characteristic case of maladaptive emotion regulation. For example, people report ruminating—i.e. perseverative, passive, self-focused thinking about one's emotional state (Nolen-Hoeksema and Morrow 1991)—after exercising as much as after a control activity. Perhaps exercise hastens emotional recovery by buffering against the prolonged negative effects of rumination without reducing the probability or frequency of rumination itself. However, it is also possible that traditional measurement and analytic approaches to studying emotion regulation oversimplify the story by reducing multifaceted negative,

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✉ Emily E. Bernstein
ebernstein@g.harvard.edu

1 Department of Psychology, Harvard University, 33 Kirkland Street, Cambridge, MA 02138, USA

2 Psychological Sciences Research Institute, Institute of Neuroscience, Université Catholique de Louvain, Place du Cardinal Mercier, 10, 1348 Louvain-la-Neuve, Belgium

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preservative response styles to a single sum score from a self-report measure. This approach treats each component of rumination as interchangeable, thereby enabling researchers to tally responses to items when examining treatment effects or group differences. Studying rumination from a different perspective may uncover psychological mechanisms of exercise's emotional benefits.

For example, Bernstein et al. (2017) applied network analytic methods to characterize post-stressor state rumination as a potentially causal system of interacting components (e.g. negativity, replaying, self-criticism) rather than as a sum of these components. Analyses revealed that component processes were unsurprisingly strongly interrelated, but also not interchangeable. When each component process of rumination was treated as its own entity, they appeared to relate to, influence, and be influenced by the others in the different ways. Notably, across three network models, self-criticism stood out as most consistently central and influential within the network (Bernstein et al. 2017). Thus, whereas prior exercise may not significantly alter rumination sum scores, it may alter certain components of rumination, such as self-criticism, or the relations among them. This perspective could offer important information about how exercise enhances well-being as well as how to intervene on emotion regulation deficits more generally.

Ruminative response styles are overwhelmingly prevalent in individuals at risk for or diagnosed with emotional disorders, and thus parsing mechanisms and devising effective, targeted interventions are both theoretically and clinically imperative. For these reasons, we examined item-level state rumination data from a larger study exploring the effects of prior aerobic exercise (cycling vs. static stretching) on self-reported emotional recovery following a stressor by using a network analytic approach. To do so, we applied network analysis to visualize and quantitatively consider aerobic exercise as an intervention acting on a system of rumination processes. We considered dimensions of rumination consistent with the response styles theory (Nolen-Hoeksema et al. 2008) and other state measures (LeMoult et al. 2013; Moberly and Watkins 2008). These included aspects of the valence (i.e. negative), content (i.e. self-referential and focused on feelings and problems or stressors), and nature (i.e. perseverative, passive) of one's thoughts following an experimental stressor. Our goal was to generate new hypotheses by identifying plausible, specific links between exercise and emotional flexibility. We estimated an undirected network depicting regularized partial correlations among components of state rumination and a directed network depicting the relative, predictive power of each node. These complementary approaches can provide a novel perspective and clues to causal connections meriting more rigorous, follow-up experimental work (Borsboom et al. 2011; Costantini et al. 2015; Schmittmann et al. 2013).

Method

Participants

Two hundred twenty-six participants (143 women, $M_{age} = 20.51$, $SD = 2.56$, age range: 18–31) were included in analyses. An additional five individuals enrolled in the study but were excluded prior to examining data due to non-adherence to the protocol, experimenter error, or technical difficulties. Self-reported race and ethnicity were as follows: 56.19% Caucasian or white, 5.75% African American or black, 20.80% Asian or Asian American, .88% Native American or American Indian, 13.72% multiracial, 2.65% other or unreported, and 14.16% identified as Hispanic or Latino. For safety and to avoid potential confounds related to extreme or unhealthy attitudes towards exercise, we only included individuals who denied being pregnant or possibly pregnant, answered "no" to every question on the Physical Activity Readiness Questionnaire (PAR-Q; Adams 1999; Thomas et al. 1992) indicating no physical or medical contraindications to exercise, and scored below the clinical cut-off (i.e. ≤ 24) on the Exercise Addiction Inventory: Short Form (EAI; Terry et al. 2004) suggesting no risk for exercise addiction. Participants were recruited through the Harvard Psychology Department Study Pool. The sample comprises undergraduate and graduate students as well as community members. The Harvard University Institutional Review Board approved the study. Participants were tested individually and provided written informed consent prior to beginning the experimental session. Demographic and clinical characteristics of the sample are presented in Table 1.

Procedure and Materials

Participants were randomly assigned to complete one of two activities: moderate cycling (aerobic exercise condition; $n = 113$) or stretching (control condition; $n = 113$). Participants then underwent a stressful speech task, followed by a recovery period. State rumination during the recovery period was measured through self-report. A description of the larger study appears elsewhere (Bernstein and McNally 2018).

Experimental Manipulation

In the exercise condition, participants cycled at a moderate pace for 30 min. This period included 5 min of warm-up and 25 min of sustained exercise at 60–70% of estimated maximum heart rate (i.e. 208 − [0.7 × Age]; Tanaka et al. 2001) on a stationary bicycle. In the stretching condition, participants completed 30-min of static stretching. They

Table 1 Demographic and clinical characteristics of the sample

Measure	Whole sample N (%)	Cycling	Stretching	Difference
Gender				$X^2 = 2.30$, $p = .13$
Female	143 (63.27)	66 (58.41)	77 (68.14)	
Male	83 (36.73)	47 (41.59)	36 (31.86)	
Ethnicity				$X^2 = 0.0$, $p = 1.0$
Hispanic/Latino	32 (14.16)	16 (14.16)	16 (14.16)	
Not Hispanic/Latino	184 (81.42)	92 (81.42)	92 (81.42)	
Unknown/not reported	10 (4.42)	5 (4.42)	5 (4.42)	
Race				$X^2 = 4.50$, $p = .61$
Asian/Asian American	47 (20.80)	26 (23.01)	21 (18.58)	
Black/African American	13 (5.75)	4 (3.54)	9 (7.96)	
Native American	2 (.88)	2 (1.77)	0 (.00)	
White/Caucasian	127 (56.19)	63 (55.75)	64 (56.64)	
Multiracial	31 (13.72)	15 (13.27)	16 (14.16)	
Other/not reported	6 (2.65)	3 (2.65)	3 (2.65)	
	M (SD)			
Age	20.51 (2.58)	20.27 (2.24)	20.74 (2.87)	$F(1,224) = 1.88$, $p = .17$
DASS-depression	6.60 (7.19)	6.04 (7.40)	7.17 (6.96)	$F(1,224) = 1.40$, $p = .24$
DASS-anxiety	5.04 (5.00)	4.74 (4.70)	5.33 (5.28)	$F(1,224) = .77$, $p = .38$
DASS-stress	11.28 (7.90)	10.73 (7.80)	11.84 (7.99)	$F(1,224) = 1.13$, $p = .29$
RRS	44.26 (12.31)	43.73 (12.62)	44.79 (12.02)	$F(1,224) = .41$, $p = .52$
SRQ	117.10 (104.52)	130.42 (105.36)	103.60 (1.02.36)	$F(1,222) = 3.73$, $p = .05$

DASS Depression Anxiety and Stress Scales-21 item, *RRS* Rumination Responses Scale, *SRQ* State Rumination Questionnaire

were periodically provided with guided stretches to complete. A Polar monitor, worn around the chest, continuously recorded heart rate in both conditions. The experimenter also monitored adherence.

Stressor

Participants completed a stressful speech task based on the Trier Social Stress Test (Kirschaum et al. 1993). Participants were instructed to imagine that they had been invited to interview for a prestigious fellowship. They were given 5 min to prepare and then delivered a 5-min speech with the topic: why you are a good friend. Participants were not allowed any notes while speaking. The experimenter watched their performance but provided no feedback. Participants then sat alone for 5 min.

State Rumination

Consistent with Bernstein et al. (2017), we analyzed five items from a modified State Rumination Questionnaire (SRQ) to capture rumination during the 5-min after the speech task (LeMoult et al. 2013). This measure was administered once at the end of the 5-min recovery period. Items included how much they had been thinking about their performance (perseveration), how negative their thoughts were (negativity), how much they had been criticizing themselves (self-criticism), how much they thought about their negative emotional experience (brooding), and to what extent they replayed parts of what happened in their mind (replaying). Answers were indicated on a visual analog scale from 1 to 100. Higher ratings indicate more rumination (e.g. more negativity). This measure had good internal consistency, Cronbach's alpha = .87. Independent sample *t* tests, using Benjamini–Hochberg procedure to adjust for multiple comparisons, revealed no group differences (cycling vs. stretching) in total sum scores or responses to any individual items, *ps* > .05.

Network Estimation and Visualization

Using the R package *qgraph* (Epskamp et al. 2012), we computed two types of networks to examine how the interrelationships among items from the SRQ could differ between individuals who had previously stretched and those who had previously cycled. These graphs have three principal features: nodes (i.e. variables or SRQ items), edges (i.e. pairwise connections between nodes), and location. Generally, nodes are positioned to visually represent the relative strength of their connections. Two nodes depicted closer together are more strongly connected and nodes depicted nearer to the center of the graph have stronger connections overall (Fruchterman and Reingold 1991). We computed two different models, each estimating edges and the importance of nodes in different ways. Multiple perspectives on the data allow us to be more confident in emerging hypotheses should a certain pattern hold across methods. Three data points were missing in the stretching group dataset; therefore, we used pairwise complete observations to estimate our models. We ran the following analyses on each group (stretching vs. cycling) separately. Although the sample size is modest for network analyses, the present models are importantly low-dimensional (i.e. few nodes relative to the number of participants), as recommended (e.g. Bernstein et al. 2017).

Graphical LASSO Networks

The first was a Graphical Gaussian Model (GGM) depicting associations among nodes, controlling for the effects of all other nodes (Epskamp and Fried 2018). Because variables were not normally distributed, we used the nonparanormal transformation in the R package *huge* (Jiang et al. 2019). We present GGMs that were regularized via the graphical LASSO (Least Absolute Shrinkage and Selection Operator). Trivially small associations from the original models, potential false positives, disappear from the graph and remaining edges depict regularized partial correlations that further limit spurious associations (Friedman et al. 2011). The *qgraph* package (Epskamp et al. 2012) also automatically implements an extended Bayesian Information Criterion (EBIC) model selection procedure (Foygel and Drton 2011). In this procedure, 100 models with varying degrees of sparsity are estimated; a final model is selected according to the lowest EBIC value, given a certain hyperparameter gamma (γ) controlling the balance between specificity (possibly excluding true edges, but eliminating false ones) and sensitivity (retaining true edges, but possibly false ones also). We set γ to 0.5 to favor a sparser model and thus minimizing the likelihood of "false alarm" edges. All edges in our models were positive. Thicker edges denote larger partial correlations. We adjusted the two layouts to be similar to ease visual comparisons.

For each graphical LASSO network, we also computed strength centrality indices (Boccaletti et al. 2006; Freeman 1978/1979) via *qgraph*. These metrics quantify the importance of each node within the overall network. Node strength is the sum of the edge weights incident on a given node, thus higher values indicate greater centrality and thus greater importance in the network. Plots depict the normalized (z-scored) strength centrality values for each node.

Relative Importance Networks

We used the R package *relaimpo* (Grömping 2006) to compute the second model, a relative importance network, which estimates edges as the contribution each node makes to R^2 after controlling for multicollinearity (Heeren and McNally 2016; McNally et al. 2015; Robinaugh et al. 2014). Edges are thus again weighted, but also directed, representing predictive directionality with arrows. A relative importance metric (*lmg*), ranging from 0 to 1, is computed for each possible edge (Grömping 2006; Johnson and LeBreton 2004). Thicker edges denote larger *lmg* values. We again adjusted the two layouts to be similar to ease visual comparisons.

For the two directed networks, strength centrality indices were divided into in-strength and out-strength. In-strength denotes the sum of edges weights arriving at a given node; nodes with high in-strength are those most influenced by all other nodes in the network. Out-strength denotes the sum of edge weights originating from a given node; nodes with high out-strength are the strongest predictors in the network.

Results

Figure 1 includes the graphical LASSO networks and strength centrality plots for the stretching and cycling groups, respectively. Changes to the role of self-criticism seem most prominent. Whereas the negativity—brooding ($r_{stretching} = .39$, $r_{cycling} = .58$) and perseveration—replaying ($r_{stretching} = .26$, $r_{cycling} = .35$) connections remain some of the strongest in both networks, self-criticism—negativity ($r_{stretching} = .31$, $r_{cycling} = .24$), self-criticism—brooding ($r_{stretching} = .22$, $r_{cycling} = .15$), self-criticism—replaying ($r_{stretching} = .29$, $r_{cycling} = .20$) and self-criticism—perseveration ($\mathrm{r}_{stretching} = .31$, $r_{cycling} = .28$) connections decrease. Such changes are echoed in the strength centrality estimates. In the stretching group, self-criticism is the strongest nodes in the network. However, in the cycling group, it falls to third.

With the *R* package *bootnet* (Epskamp et al. 2018), we bootstrapped confidence regions of the edge weights by using a non-parametric approach and sampling data with 1000 replacements to estimate the accuracy of the networks. The edges were reasonably stable and 70% of edges in the stretching network and 40% of the edges in the cycling network exhibited values greater than zero. See Figure S1 in Supplemental Materials. We also used a subset bootstrap procedure in the *R* package *bootnet* (Epskamp et al. 2018) to examine the stability of strength centrality indices

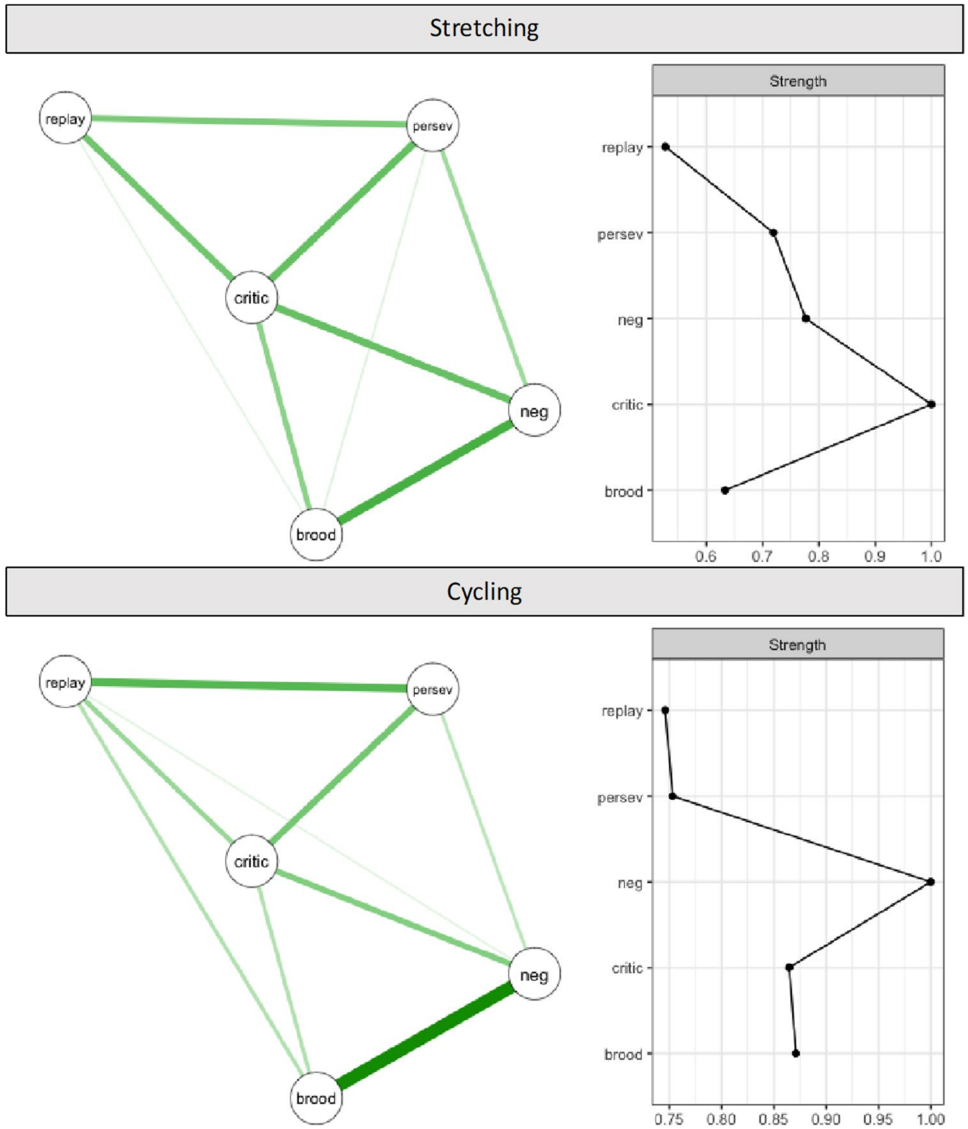

Fig. 1 Graphical LASSO networks and strength centrality plots. *Note*. Edge weights reflect relative strength of associations (all positive). Plots show strength centrality, or the sum of the edge weights connecting a given node to other nodes. Persev = perseveration or "How much have you been thinking about your performance?". Neg = negativity or "How negative have your thoughts been?". Critic = self-criticism or "How much have you criticized yourself about your performance?". Brood = brooding or "How much have you thought about how upset you felt?". Replay = replaying or "To what extent did you replay parts of what happened in your mind?"

(Costenbader and Valente 2003). In this procedure, strength centrality metrics are repeatedly correlated with new metrics calculated from an increasingly small subsample of participants (1000 person-dropping bootstraps). If correlation values decline substantially as participants are removed, centrality estimates are deemed insufficiently stable. Correlations remained large (> .50) with up to roughly a quarter of the sample removed. See Figure S2 in Supplemental Materials.

Figure 2 depicts the relative importance networks and strength centrality plots for the stretching and cycling groups. The overall structure of the network appears preserved between the two groups. Although in-strength estimates remain unchanged between the two groups, it is the drop in out-strength of self-criticism that seems to differentiate the networks. For example, in the stretching condition, self-criticism strongly predicted brooding (*lmg* = .31), negativity (*lmg* = .34), perseveration (*lmg* = .37), and replaying (*lmg* = .39). In the cycling condition, the edge from self-criticism is weakened for brooding (*lmg* = .21), negativity (*lmg* = .24), perseveration (*lmg* = .32), and replaying (*lmg* = .26). Similar to the Graphical LASSO, negativity had the highest in-strength and out-strength values in the network. We also bootstrapped confidence regions of the directed edge weights with the *R* package *bootnet* (Epskamp et al. 2018) by using a non-parametric approach

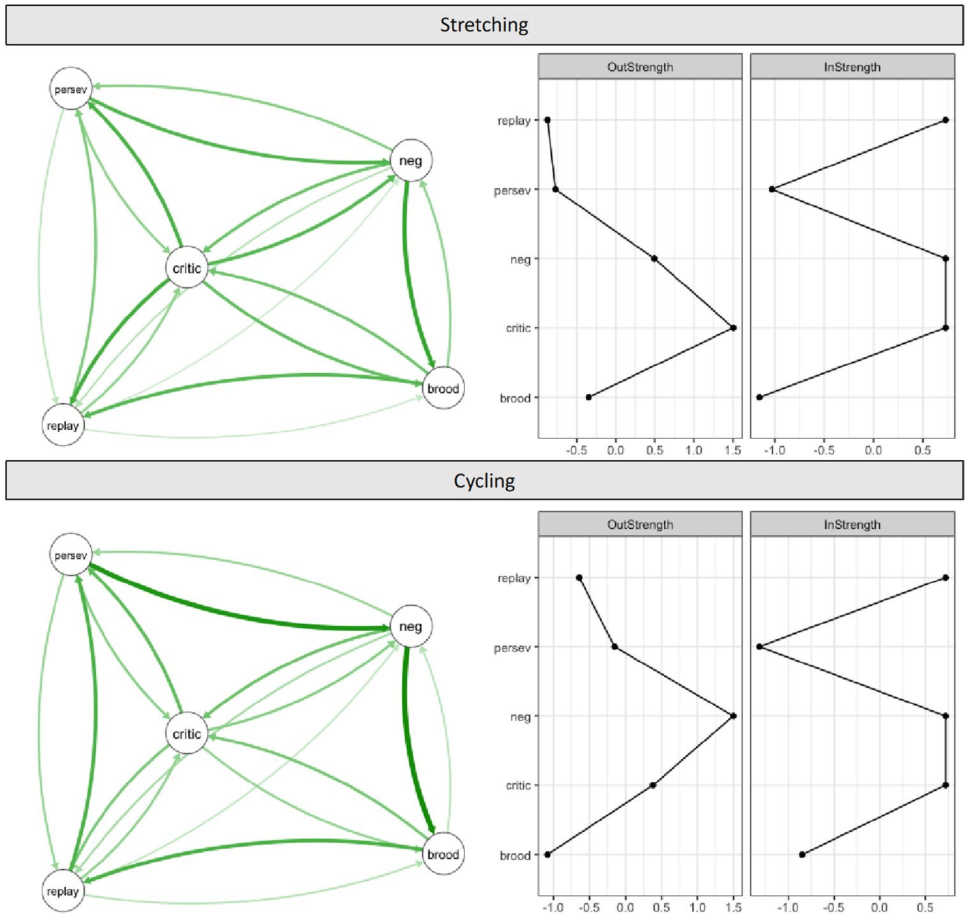

Fig. 2 Relative importance graphs and strength centrality plots. *Note*. Relative importance networks in which edge weights reflect relative contribution the predictor makes to R^2 and arrows denote predictive directionality. Centrality plots: In-strength = sum of the directed edge weights originating from other nodes and ending at a given node. Out-strength = sum of the directed edge weights originating from a given node and ending at other nodes. Persev = perseveration or "How much have you been thinking about your performance?". Neg = negativity or "How negative have your thoughts been?". Critic = self-criticism or "How much have you criticized yourself about your performance?". Brood = brooding or "How much have you thought about how upset you felt?". Replay = replaying or "To what extent did you replay parts of what happened in your mind?"

and sampling data with 1000 replacements. All edges were stable. See Figure S3 in Supplemental Materials.[1]

Discussion

We used network analytic approaches to explore new questions as to how exercise affects emotion regulation and consequently emotional well-being. Whereas traditional reports of rumination after the speech task, i.e. sum scores, did not differ between the stretching and cycling groups, networks visualizing the state rumination items lead to two hypotheses about exercise's effect on rumination. Encouragingly, the graphical LASSO and relative importance networks, which have complementary strengths, limitations, and assumptions, converged in the following patterns. This bolsters our confidence that results from this preliminary study merit further investigation.

Apparent changes to the role of self-criticism within the networks between the stretching and cycling groups stood out. It is not that participants in the cycling group necessarily reported less self-criticism overall than those in the stretching group. Rather, there appear to be changes in how self-criticism relates to other component processes. For example, whereas brooding—negativity and perseveration—replay remained two of the strongest, most stable edges across both networks, criticism—replaying and criticism—brooding dropped in strength and stability in the cycling network. Self-criticism was highly influential in the stretching graphical LASSO and relative importance networks, evinced by its high strength centrality in the former and high out-strength centrality in the latter. This is consistent with prior network analyses of these state rumination items (Bernstein et al. 2017) and suggests that the degree to which individuals criticize themselves may activate or maintain other processes (e.g. brooding) and the larger rumination network.

[1] As a final exploratory analysis, we employed a novel approach in which condition was included as a dichotomous node within the network (e.g., Blanken et al. 2019; Kraft et al. 2019). Results revealed that condition did not share a statistically significant edge with any rumination node, suggesting that group assignment did not affect the level of any given rumination component. Self-criticism remained the most central node in this updated model. Note that this new analytic approach was developed to examine treatment effects across time, rather than between group differences at single time points as was done in the present paradigm. This approach may be more appropriate for examining the existence and course of longitudinal effects of exercise as an intervention for rumination.

High out-strength is frequently interpreted to mean that a node could be a promising target for intervention (McNally 2016). If it is confirmed that such a node is a driving force, lessening it could deactivate other nodes and beneficially weaken the network. The present data supports this hypothesis. Though cross-sectional and therefore unable to confirm causal connections, our data suggest that acute aerobic exercise could have weakened the self-criticism node; it is plausible that this, at least in part, hastened emotional recovery from the stressor relative to the stretching control condition. In this way, measuring the content of a rumination bout (e.g. degree of self-criticism) may be particularly important when studying or intervening on this response style.

Our study has limitations. Most importantly, it was not designed for network analyses and therefore was insufficiently powered to do a formal network comparison test (Van Borkulo et al. 2015). Observed differences in global strength, individual edges, or patterns between the networks should thus be treated as hypotheses to be tested. A replication with many more participants would be required to confirm the statistical significance of the observed differences. Furthermore, time series data would also us to examine the hypothesized causal and temporal connections between nodes. Second, participants in this study were not selected for clinical symptoms, thus severe levels of rumination are likely underrepresented. However, the sample was heterogeneous, with 32.30% of participants reporting at least moderate symptoms of depression, 42.48% at least moderate symptoms of anxiety, and 57.86% at least moderate symptoms of stress on the Depression Anxiety Stress Scales, 21-item (DASS-21; Lovibond and Lovibond 1995). Furthermore, rumination is also not unique to clinical populations and is a general risk factor for emotional disorders (McLaughlin and Nolen-Hoeksema 2011); thus, examining this problematic response style at varying levels of severity is worthwhile. Still, replicating results in an explicitly clinical sample, or exploring differences therein, is a necessary extension of this work. In addition, the present study compares cycling to stretching as its control condition. However, stretching may also affect network structure, and different results could emerge with other forms of physical activity. Thus, a replication including an inactive control condition and varying physical activities would also help to clarify results. Finally, statistical tools—including network analyses—only consider variables that are included in a given model. Although parsimonious graphs, like those presented here, are helpful for interpretation and hypothesis generation, it is always possible that critical other variables were omitted. Thus, the inclusion of additional, important variables (e.g. behavioral tasks, symptoms) could further improve our understanding of rumination and its consequences.

Overall, results from this exploratory study highlight a potential pathway through which even a single session of exercise affords emotional benefits. This novel perspective merits further experimental exploration and supports claims that exercise bolsters emotion regulation and thus emotional resilience or flexibility, rather than simply elevating mood or preventing the occurrence negative emotional shifts. Future work should explore mechanisms to account for these effects. For example, aerobic exercise training can hasten physiological recovery from stress, lessen HPA axis reactivity, and increase production of brain-derived neurotrophic factor (e.g. Puterman et al. 2011; Szuhany et al. 2015); such biological changes could increase resilience and create a buffer against prolonged emotional stress. Effects could also have more psychological bases as well. For example, aerobic exercise may be related to more mindful or acceptance-oriented mindsets and balanced appraisals (e.g. Mothes et al. 2014; Ulmer et al. 2010). Thus, ruminative thoughts could have been slowed down in the cycling group or contrasted with other less critical appraisals of the situation, and self-critical thoughts could have had less of an impact on participants relative to the stretching group. Relatedly, accomplishing a challenging task, such as cycling, could induce feelings of mastery or heightened self-esteem that prevent self-critical thoughts about the speech task from spiraling or inducing other ruminative processes.

Findings also reiterate prior assertions that although strongly related, components forming the rumination construct are not interchangeable. Rumination may be a helpful term for summarizing a person's general response style, but it may be less useful than its parts when studying mechanisms or interventions (cf. Fried and Nesse 2015; Fried et al. 2014). A single sum score occluded what could be meaningful differences in rumination following aerobic exercise. This work highlights how the network approach can be used to generate and test new hypotheses for experimental and intervention research. These visualizations can help to identify plausible causal structures within a system of emotions, symptoms, or processes, and point to nodes that when targeted may produce broad beneficial, clinical changes.

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Data Availability Data are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Conflict of Interest Author Emily E. Bernstein, Author Alexandre Heeren, and Author Richard J. McNally declare that they have no conflicts of interest.

Ethical Approval All procedures performed were in accordance with the ethical standards of Harvard University's Committee on the Use of Human Subjects and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Animal Rights Statements No animal studies were carried out by the authors for this article.

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