

RESEARCH ARTICLE

Creative challenge: Regular exercising moderates the association between task-related heart rate variability changes and individual differences in originality

Christian Rominger^{1*}, Ilona Papousek¹, Andreas Fink¹, Corinna M. Perchtold¹, Helmut K. Lackner², Elisabeth M. Weiss¹, Andreas R. Schwerdtfeger¹

1 Department of Psychology, University of Graz, Graz, Austria, **2** Otto Loewi Research Center, Section of Physiology, Medical University of Graz, Graz, Austria

* christian.rominger@uni-graz.at



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Abstract

Coping with mental challenges is vital to everyday functioning. In accordance with prominent theories, the adaptive and flexible adjustment of the organism to daily demands is well expressed in task-related changes of cardiac vagal control. While many mental challenges are associated with increased effort and associated decreased task-related heart rate variability (HRV), some cognitive challenges go along with HRV increases. Especially creativity represents a cognitive process, which not only results from mental effort but also from spontaneous modes of thinking. Critically, creativity and HRV are associated with regular exercising and fitness. Furthermore, the cross-stressor adaptation theory suggests that changes in cardiac reactions to physical challenges may generalize to mental challenges. In line with this idea the amount of regular exercising was hypothesized to moderate the association between HRV changes and creativity. A sample of 97 participants was investigated. They reported the amount of regular exercise and their ECG was measured at baseline and during a creativity task. An association between task-related HRV changes and originality as a function of participants' amount of regular exercise was found. Participants reporting more regular exercising produced more original ideas when they had higher HRV increases during the task, while more sedentary participants showed the opposite association. Results suggest that individuals with a higher amount of regular exercise achieve higher originality probably via the engagement in more spontaneous modes of thinking, while more sedentary people may primarily benefit from increased mental effort. This supports the conclusion that higher creativity can be achieved by different strategies.

Introduction

Diverse mental challenges are a major part of daily life, and the flexible adjustment to these day-to-day demands seems mandatory for successful coping [1]. However, this adaptive ability

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of self-regulation greatly varies between people and situations. Notably, mental effort, stress, and self-regulation are indexed by functions of the vagus nerve as the primary part of the parasympathetic nervous system [1–5]. A putative physiological marker of vagal control is the beat to beat variation in heart rate, the so-called heart rate variability (HRV) [6,7]. The vagal influence on HRV can be quantified in the time domain by means of RMSSD (root mean square of the successive difference in normal sinus beat intervals) and pNN50 (percentage of adjacent normal sinus beat intervals that differ by more than 50 ms) [8–10].

While the tonic HRV level potentially indicates an inter-individual trait like capacity to adapt to environmental challenges by parasympathetic/vagal control [11–13] (for a meta-analysis see [14]), task-related HRV changes represent the dynamic task-specific vagal control of the heart (i.e., vagal break) [2,15]. Therefore, task-related HRV is an even more sensitive variable in the context of regulatory efforts of the organism and the actual flexible adaption to physical and mental challenges [2,3,6,7,13,16,17]. Following from this, the adjustment of the organism to task-related challenges—e.g., self-regulatory efforts [4,13]—may be best represented by the flexible change of the HRV from a baseline to a period of mental effort.

However, not every mental challenge requires the same amount of cognitive and regulatory capacity [18,19]. Of note, while many mental tasks are associated with task-related HRV decreases [16,20,21], there is evidence that some cognitive tasks are associated with task-related increases [3,4,15]. For instance, Butler et al. [13] found HRV increases during the reappraisal of negative events [22,23], and Silvia et al. [24] reported a slight rise of vagal control during a creative ideation task. This is remarkable, since creative ideation and cognitive reappraisal (the latter as an instance of “creativity in an affective context” [25]) represent complex self-regulatory cognitive processes (e.g., flexible switch between associative and executive functions), which share important basic cognitive functions [25–28].

A unique characteristic of creative and divergent thinking tasks in contrast to traditional convergent cognitive tasks is the interplay of associative/spontaneous modes of thinking and executive top-down control processes [29–34]. Following dual process theories, creative ideation is not solely based on mental effort, which is associated with HRV decrease [24,35–38], but also on spontaneous, automatic, associative, and relaxed modes of thinking, which are presumably associated with HRV increase [39–42]. Furthermore, the flexible shift between these different modes of thinking is important for creative ideation performance [43–45]. The contribution of both modes of thinking to creative ideation may explain contradictory findings in literature. Loudon and Deininger [35] reported a negative and Bowers and Keeling [40] a positive association between indices of creative performance and HRV. Silvia et al. [24] found no significant link between task-related vagal control and originality.

However, a further reason for inconsistent findings in this context might be that cognitive performance and HRV are associated with the amount of regular physical exercise, physical fitness, and general health of people [6,8,46] (for cognition see [47,48]; but see [49]; for cognition and HRV see [50]). Furthermore, in a recent study, Latorre Román et al. [51] found an association between measures of physical fitness and creativity (see also [52,53]; similar findings for acute physical activity see, [54–56]). The cross-stressor adaptation theory [57] assumes that salutary cardiovascular reactivity and recovery due to physical training generalize from ergogenic challenges to psychogenic challenges. This generalization may lead to a differentiation of cardiac reactivity to psychological stressors between people doing more and people doing less exercise and people who might therefore be more or less physically fit [46,58–60].

Following this idea, the present study examined whether regular exercising may moderate the association between task-related HRV changes and the performance outcome in a creative ideation task. People regularly exercising more are supposed to be physically best prepared to show adaptive task-related changes of HRV [6], in order to flexibly match the adaptive states

important for optimum performance outcome [1]. More precisely, it was assumed that participants with a higher amount of regular exercise may more flexibly adjust to the creative challenge and more easily switch between mental effort [24,35] and spontaneous and automatic modes of thinking [40–42]. Therefore, it was hypothesized that participants exercising more often will show higher task-related HRV during creative ideation in contrast to participants exercising less, and that in exercisers (but not necessarily in sedentary people) the HRV response will be related to task performance.

Methods

Participants

An a-priori power analysis was conducted using the software G*Power 3.1 [61]. The analysis indicated that a sample size of 99 participants is required to detect a medium effect ($f^2 = .15$) with a power of .80 and an alpha error of 5%. One hundred and two people were recruited to participate in the study because of potential technical failures and dropout from the study. Due to recording problems of the electrocardiogram two participants were excluded. Two further participants did not comply with the instructions, and another participant was excluded because of excessive artifacts in the recorded ECG. The final sample consisted of 97 participants (54 women) with an age range from 18 to 33 years ($M = 23.07$ years; $SD = 3.48$ years). Participants' age range was restricted to control for potentially confounding influences on HRV [15].

People with a history of major psychiatric disorders according to the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID) and people, who reported having a neurological disease or using psychoactive medication were not included in the study. All participants were right-handed (assessed by a standardized hand skill test; [62]). They were requested to refrain from alcohol intake for 12 h and from drinking coffee and other stimulating beverages for 2 h prior to their appointment, and to come to the session well rested. The study was approved by the Ethics Committee of the University of Graz, approval number GZ. 39/41/63 ex 2015/16. Written informed consent was obtained from all participants.

Amount of regular physical exercise

The Freiburger Questionnaire on Physical Activity (FQPA) [63] is a reliable and valid self-report instrument, which covers everyday physical activities (e.g., walking to work), leisure time activities (e.g., dancing), and sports activities (e.g., swimming) [64,65]. Participants are instructed to indicate the duration for each activity in minutes per week which are converted into metabolic equivalents (MET) [66]. In order to derive a measure of physical exercise potentially resulting in higher bodily fitness [67], only the reported hours of sports activity per week (e.g., running, playing soccer, swimming, $M = 3.41$ h, $SD = 3.68$ h) were considered (exercise MET: $M = 22.16$, $SD = 26.12$) [68]. Frey et al. [63] reported a re-test reliability of $r = .98$ (two weeks) for the amount of exercise per week.

Creative thinking task and task performance

The Alternate Uses (AU) task [69] is a verbal creativity/divergent thinking test used in numerous scientific studies [24,30,70]. The participants' task was to generate alternative uses of common objects (e.g., umbrella, brick, or key). For the present investigation, a single answer (i.e., best idea) and self-paced version of the AU task was used. This approach was applied in order to more strongly focus on the originality aspect of creativity [26]. The self-paced procedure appropriately captures the spontaneous nature of the creative thinking process [71–75];

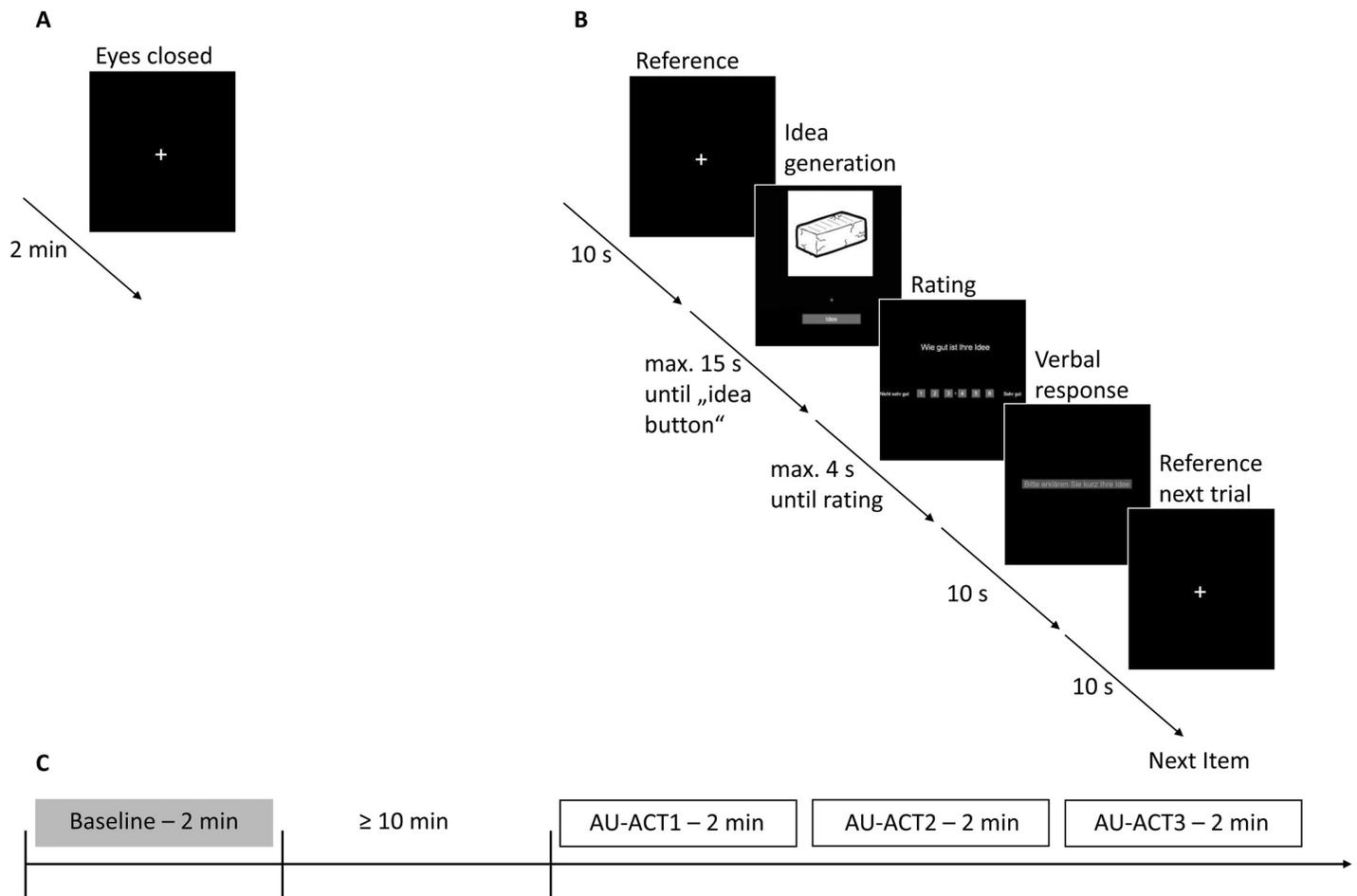


Fig 1. Schematic time course of the computerized (A) baseline, (B) AU task, and (C) the analysed 2 minutes time periods (Baseline, AU-ACT1, AU-ACT2, AU-ACT3).

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however, it also implicates high demands on self-regulatory mechanisms. Each trial started with a white cross (10 s), followed by a picture of a common object (idea generation phase with a max. response time of 15 s; see Perchtold et al. [26] for a similar procedure). After the “idea button” was pressed, the participants rated the originality of their idea on a 6-point Likert-scale (max. response time of 4 s) and finally voiced the idea (10 sec). The subjective rating was included to maintain the participants’ effort to produce high quality ideas for every single item of the task. With the presentation of a new fixation cross the next trial started (see Fig 1 for an illustrative summary of the time course of the task). Sixteen objects were presented in randomized order.

The voiced ideas were transcribed and rated by three independent and trained raters on a four-point Likert scale ranging from “not original” to “very original”. This procedure is a common approach in creativity research (cf. Consensual Assessment Technique; [30,76]). The originality ratings showed acceptable interrater reliability ($ICC(2, k) = .66$).

Procedure

All participants were tested individually. The recording took place in a separate and quiet room, where participants were seated in a comfortable chair. During the recordings, they were monitored via a web cam to ensure that they were following the instructions. After filling in

the consent form, participants filled in the questionnaire assessing the amount of regular physical exercise. Then, the ECG was applied, and the baseline was recorded for two minutes. Participants were told to relax and keep their eyes closed until they heard a signal tone. After that, participants worked on tasks not relevant for the study question, which lasted a minimum of 10 minutes (see Fig 1). Then, the AU task followed.

Recording and quantification of HRV

The electrocardiogram was recorded using a standard limb lead II electrode configuration with a sampling rate of 500 Hz (Brainvision Research Amplifier, Brain ProductsTM). The ECG signals were manually checked for artifacts by means of the software Kubios HRV Premium version 3.0.2. The mean heart rate of the participants at the baseline level was 68.61 bpm ($SD = 11.11$ bpm). HRV was quantified in the time domain by means of the root mean square of successive differences of the successive RR intervals. RMSSD has been shown to sensitively index vagal efference [77] especially during cognitive processes [21]. RMSSD was calculated for the two minutes baseline interval and three consecutive two minutes periods during the creative ideation task, starting from the onset of the first white cross (see Fig 1). Two minutes are considered adequate to evaluate RMSSD reliably [9,15,78]. As depicted in Fig 1, the three two minutes periods of the creative thinking task were calculated for comparability reasons with baseline ([9,15]; similar procedure see, [24,60,79]). The pooled untransformed RMSSD value of the three activation periods was $M = 49.43$ ms ($SD = 24.57$ ms) and the baseline was $M = 51.63$ ms ($SD = 27.25$ ms). The RMSSD reactivity showed high variability, with both increases and decreases ($M = -2.20$ ms, $SD = 13.24$ ms, $min = -49.13$ ms, $max = 28.12$ ms).

Furthermore, to control for respiration-induced changes in HRV, ECG derived respiration (EDR) was calculated by means of software Kubios HRV Premium version 3.0.2 for the baseline ($M = 0.23$ Hz, $SD = 0.04$ Hz) and the three consecutive two minutes activation periods, which were pooled together ($M = 0.23$ Hz, $SD = 0.03$ Hz).

On average, participants completed 11.73 ($SD = 1.78$) items during the three activation periods of overall 6 minutes ($min = 6$ items, $max = 14$ items). The range of response times from item onset to activation of the “idea button” was between 2933 ms and 12 329 ms ($M = 6522$ ms, $SD = 2231$ ms).

Statistical analysis

Because of the skewed distribution of the RMSSD values, which was visually checked, a transformation with the natural logarithm (\ln) was performed for all conducted statistical analyses [15,80–82].

Firstly, to explore the overall challenging effect of the creative thinking task, a one-way analysis of variance with the within-subjects factor TIME (Baseline, AU-ACT1, AU-ACT2, AU-ACT3) and the HRV (\ln RMSSD) as the dependent variable was calculated. Due to violations of sphericity assumptions, the multivariate approach was used [83]. To illustrate the interindividual differences in HRV changes, the untransformed RMSSD values were presented.

The main research question, if regular exercising moderates the association between task-related HRV changes and creative ideation performance outcome, was evaluated using standard multiple regression analysis with the task-related HRV change score, the amount of physical exercise, and the interaction term as predictors, and task performance (originality) as the dependent variable. The task-related HRV change score was calculated by regressing the baseline \ln RMSSD values on the pooled \ln RMSSD values of the three two minutes activation periods (AU-ACT1, AU-ACT2, AU-ACT3) [84]. This procedure results in one residualized

change index with higher scores indicating a relative increase in HRV and lower scores indicating a relative decrease in HRV during the creative ideation task. To illustrate the significant interaction effect of physical exercise and task-related HRV changes on originality, predicted originality was calculated for one standard deviation below sample mean ($M - 1$ SD) and one standard deviation above sample mean ($M + 1$ SD) using standard regression analysis (similar procedure see e.g., [85,86]). To control for respiratory-induced changes in HRV, this standard multiple regression analysis was re-run with the mean EDR frequency of the three activation periods as an additional predictor.

All analyses were calculated by means of IBM SPSS Statistics 25 for windows and the significance level was set to 5%.

Results

Overall effect of the creative thinking task on HRV

The analysis slightly failed to reach a significant main effect for TIME ($F(3,94) = 2.45, p = .069, \eta_p^2 = .03$). As indicated in Fig 2, the strongest decrease of HRV was from baseline to the first interval of the creative ideation task.

Association between task-related HRV (lnRMSSD) change and task performance (originality), and its moderation by the amount of regular exercise

The regression analysis was significant ($F(3,93) = 4.50, p = .005, R^2 = .127$). As depicted in Table 1, the interaction effect of task-related HRV change by amount of physical exercise was significant ($\beta = .34, p = .001$), however the main effects of the amount of exercise and HRV change were non-significant. Please note that the results of the multiple regression analysis remained virtually the same when using pNN50 instead of RMSSD ($F(3,93) = 2.98, p = .035, R^2 = .09$).

To further qualify the interaction effect in the whole sample, the regression analysis was re-run with the amount of regular exercise set as low ($M - 1$ SD) and high ($M + 1$ SD; simple slopes approach), respectively. As illustrated in Fig 3, participants exercising more often performed better in the creative thinking task in terms of originality when they showed greater relative HRV increases during the challenge ($\beta = .40, t(93) = -2.73, p = .008$). In participants exercising less this association was reversed ($\beta = -.28, t(93) = -2.13, p = .036$).

The regression analysis with the additional predictor EDR frequency was again significant ($F(4,92) = 4.20, p = .004, R^2 = .155$). The interaction effect of task-related HRV change by amount of physical exercise remained significant ($\beta = .32, p = .001$) and the EDR frequency was not significant ($\beta = .13, p = .214$).

The correlation between the originality score and the number of generated ideas during the six minutes activation period was $r = .05$ ($p = .596$), indicating that the effects of the regression analysis was also not influenced by the number of generated ideas.

Discussion

The aim of this study was to examine the interplay of regular physical exercise and HRV reactivity during a challenging creative ideation task on task performance. Generally, HRV tended to decrease during the task, particularly at the beginning, which indicates the mobilization of mental effort and is characteristic of challenging performance tasks [87,88]. However, participants greatly varied in their cardiac response to the challenge. While some showed marked decreases of HRV, others exhibited smaller decreases or even increases of HRV during the task

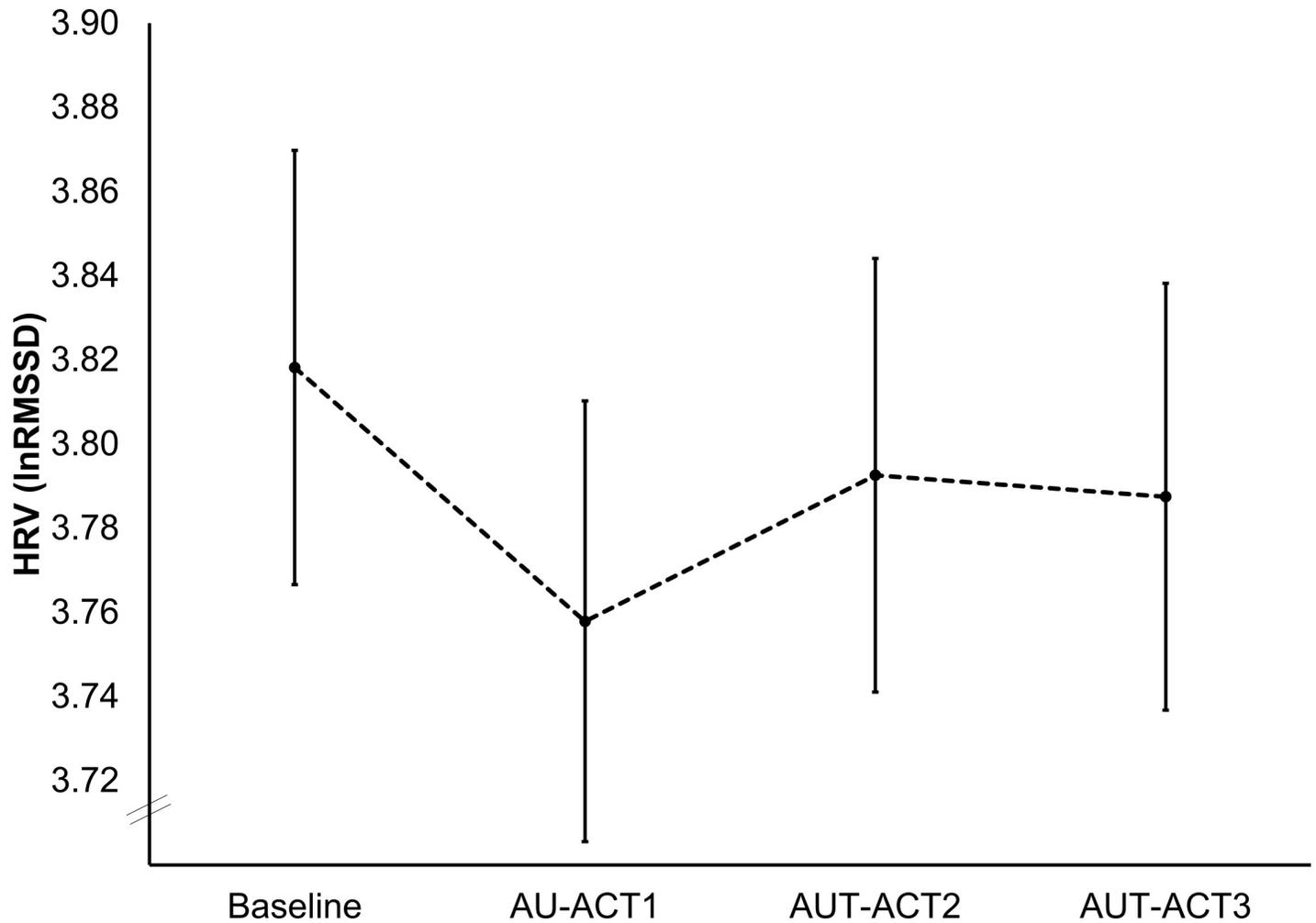


Fig 2. Mean HRV (lnRMSSD; error bars = SE) in the baseline and the three consecutive activation (ACT) intervals during the AU task (AU-ACT1, AU-ACT2, AU-ACT3).

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[15]. This variability in the cardiac responses was meaningfully related to task performance in terms of the originality of generated creative ideas. However, only when inter-individual differences in regular exercising were considered.

In people with a higher amount of regular exercise, greater HRV increase (i.e., vagal activation) during the creative ideation task was correlated with greater originality of the produced ideas, which is in accordance with some relevant research [40,41]. By contrast, in more

Table 1. Summary of the results of the multiple regression analysis for the prediction of task performance (originality) with task-related HRV (lnRMSSD) change, physical exercise, and the interaction term as predictors.

	β	r
Task-related HRV (lnRMSSD) change	.06 (.538)	.02 (.834)
Physical exercise	-.09 (.381)	-.13 (.194)
Task-related HRV (lnRMSSD) change x Physical exercise	.34 (.001)	.34 (.001)

Note. p -values in parenthesis. r represents the zero-order correlation and β the standardized Beta coefficient.

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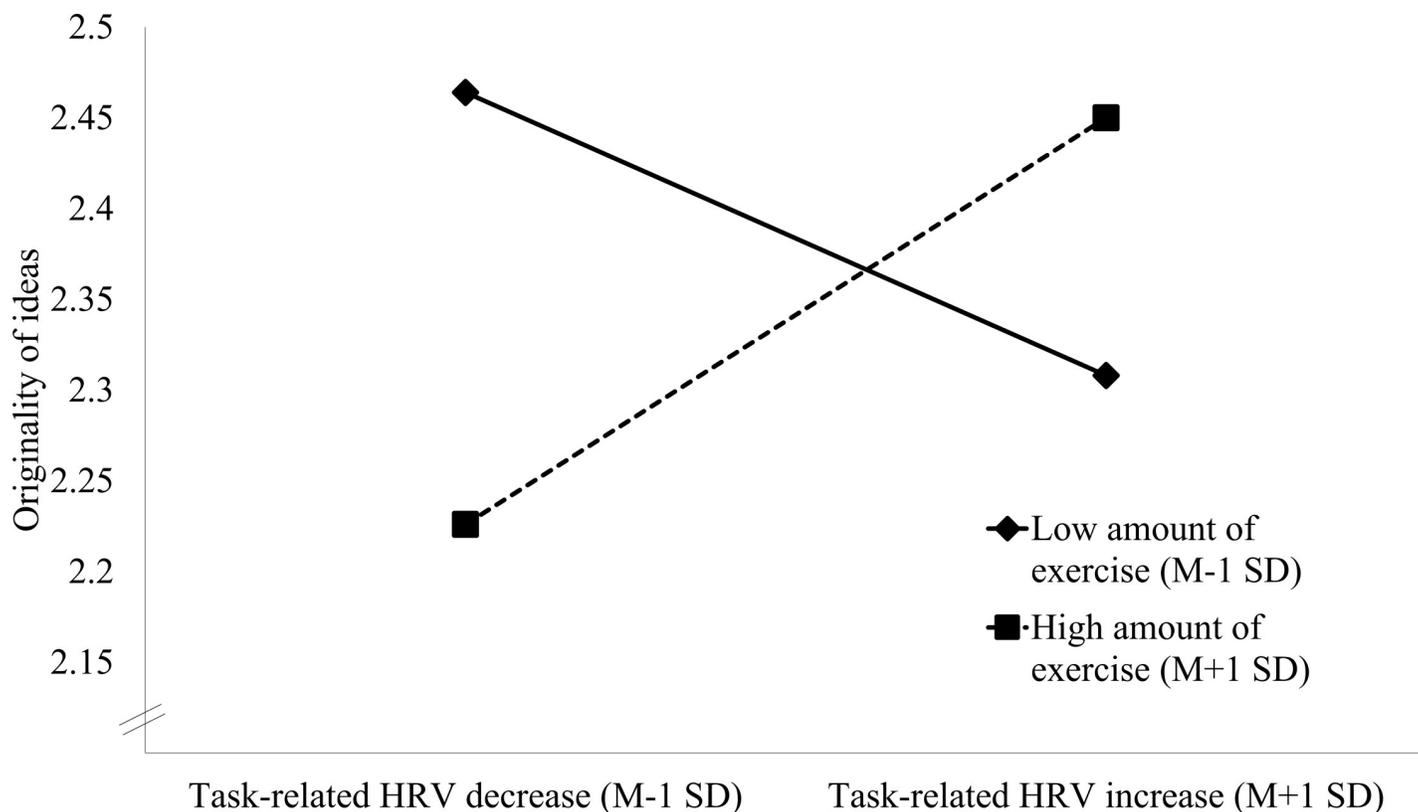


Fig 3. Interaction effect of task-related HRV change and the amount of regular physical exercise on task performance in terms of originality.

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sedentary people this association was reversed. Greater task-related HRV decrease (i.e., greater vagal withdrawal) was associated with better task performance in terms of originality, which is in line with other studies in the literature [35]. Importantly, regular exercising as such was not correlated with task performance, that is, on average, people exercising both more or less achieved similar levels of originality [52,89]. This null finding might take place because of study-design divergences. Contrary to former studies [51,53], we used a self-report measure of regular physical exercise [52]. Furthermore, while Gondola and Tuckman [53] reported increases in the fluency parameter of the AU task and Latorre Román et al. [51] found a positive effect for a composite score of multiple creative thinking tasks, we operationalized creativity by means of originality of ideas.

Nevertheless, the observed interaction effect suggests that greater originality in a creativity task is not only achieved by the investment of more mental effort [24,35], and more spontaneous and associative modes of thinking [32], but that both can lead to success, depending, among others, on the physical constitution of the person. This finding may in part explain the heterogeneity of previous results on associations between cardiac vagal control and creative performance [24,35,40].

Furthermore, the observed moderation effect at least in part supports assumptions of the cross-stressor adaptation theory [57], according to which changing cardiac response patterns to physical stressors by physical exercising may translate to altered modes of responding of regulation functions when confronted with psychological stressors [46,59,60]. People who generate more original ideas showed smaller vagal withdrawal (or even increases in heart rate variability) during task performance, when they were regularly exercising as compared to being

more sedentary. This is in line with Park et al. [90], who reported task-related increases of HRV during a cognitive task in participants with higher flexible regulation functions (i.e., higher tonic vagal control) and decreases in participants with lower regulation functions (for short review see [15]).

The present findings need to be discussed in light of some limitations. First, the amount of regular physical exercise was only assessed by self-report and not by a behavioral index. Although the current findings need to be replicated with objective measures, similar self-reports of exercise have proven suitable to reveal reliable and meaningful associations with challenge-related cardiac responses [59]. Second, it might be proposed that HRV is influenced by verbal responses during the creative ideation task [91]. However, even if the vocalization of ideas has an impact on HRV, this cannot explain the reported associations between HRV and originality (for people exercising more or less, respectively), since the number of generated ideas (within the 6 minutes activation period) was virtually independent of task performance (originality). This is further in line with the result, that the respiration frequency (EDR) had no significant impact on the findings of this study. Third, although the eye closed baseline condition is the most frequently used approach in psychophysiological research [15], an additional baseline using an eyes open condition might have been valuable to evaluate the specificity of reported task-related HRV changes. Fourth, due to the cross-sectional, correlational nature of the present study, no cause-effect relationship can be deduced from the results.

Despite of these limitations, the findings of this research suggests that participants exercising more often in their daily life achieve higher originality with more flexible, associative, and spontaneous modes of thinking, while participants exhibiting a more sedentary lifestyle more strongly invest mental effort to reach the same quality level of produced ideas. Since solving open and ill-defined problems constitutes a daily mental challenge for many people such mechanisms might impose health risks and lower well-being in people with a sedentary lifestyle in the long run. Conversely, grounding on the cross-stressor adaptation theory the findings of the present research supports the beneficial effect of regular exercising on mental challenges in daily life [46,57].

Conclusions

The current study provides evidence that creative performance depends on individual differences in task-related changes in vagal activity, when taking regular exercising into account. This supports the conclusions that firstly, regular physical exercising has an impact on creativity [51,53] and secondly, higher creativity can be achieved by different strategies such as spontaneous modes of thinking and mental effort [24,32].

Supporting information

S1 Dataset.
(XLSX)

Author Contributions

Conceptualization: Christian Rominger, Ilona Papousek, Andreas R. Schwerdtfeger.

Data curation: Christian Rominger, Corinna M. Perchtold.

Formal analysis: Christian Rominger.

Funding acquisition: Ilona Papousek.

Methodology: Christian Rominger, Ilona Papousek, Andreas Fink, Corinna M. Perchtold, Helmut K. Lackner, Elisabeth M. Weiss, Andreas R. Schwerdtfeger.

Project administration: Ilona Papousek.

Writing – original draft: Christian Rominger, Ilona Papousek, Andreas R. Schwerdtfeger.

Writing – review & editing: Andreas Fink, Corinna M. Perchtold, Helmut K. Lackner, Elisabeth M. Weiss.

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