Czarnek, G, Richter, M and Strojny, P

Cardiac Sympathetic Activity During Recovery as an Indicator of Sympathetic Activity during Task Performance

This is the peer reviewed version of the following article: Czarnek, G., Richter, M., & Strojny, P. (2020). Cardiac sympathetic activity during recovery as an indicator of sympathetic activity during task performance. Psychophysiology, which has been published in final form at https://doi.org/10.1111/psyp.13724. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

Cardiac Sympathetic Activity During Recovery as an Indicator of Sympathetic Activity during Task Performance

Authors

Gabriela Czarnek[1,2], Michael Richter[3], Paweł Strojny[1,4]

[1] Nano Games, Cracow (Poland)

[2] Institute of Psychology at Jagiellonian University, Krakow (Poland)

[3] School of Psychology at Liverpool John Moores University, Liverpool (UK)

[4] Faculty of Management and Social Communication at Jagiellonian University, Krakow (Poland)

Running head: *Cardiac Sympathetic Recovery*

Abstract

The goals of this research were to analyze cardiac sympathetic recovery patterns and evaluate whether sympathetic cardiac responses to a task challenge can be predicted using residual cardiac activity measured directly after the task (that is, during the recovery period). In two studies (total *N* = 181), we measured cardiac sympathetic activity, quantified as pre-ejection period (PEP) and RB interval, during both task performance and the 2-minute recovery period following the task. Additional analyses examined effects on RZ interval. We found that sympathetic recovery from a task was rather quick: Cardiovascular recovery occurred within the first 30 seconds of the recovery period. Nevertheless, residual cardiac activity during the recovery period had predictive power for task-related cardiac activity. This suggests that sympathetic cardiac activity during recovery may serve as a useful indicator of task-related cardiac sympathetic activity. We discuss the implications of these findings for practical applications and the design of future studies.

Keywords: post-task recovery, sympathetic cardiac activity, pre-ejection period, RB interval, RZ interval

1. Introduction

The goal of this research was two-fold: (1) describing patterns of cardiac sympathetic recovery and (2) examining the usefulness of post-task recovery cardiac activity to determine levels of activity in the preceding task. Regarding the first goal, cardiac sympathetic recovery, in contrast to vagal recovery, has been largely overlooked in past research. Thus, this research fills this gap by providing findings on the recovery patterns of indices of beta-adrenergic cardiac activity such as pre-ejection period (PEP) and RB interval—we also analyzed recovery patterns of RZ interval. Furthermore, recording the physiological signals that are required to assess sympathetic activity can be difficult and these signals are prone to artifacts (e.g., Cybulski et al., 2007). Consequently, there are multiple situations in which it is very difficult or even impossible to reliably measure sympathetic cardiac activity during a task. Thus, a second goal of the current research was to verify whether focusing on post-task activity could be a solution to this problem. Specifically, we examine whether changes in cardiac sympathetic activity in response to a task challenge can be predicted using residual cardiac activity during the post-task recovery period.

1.1. Sympathetic cardiac reactivity

There are several non-invasive indicators of beta-adrenergic sympathetic influence on the heart such as PEP, RB, and RZ interval (see Figure 1). Probably the most frequently used is PEP, which is the interval between Q-onset (the beginning of left ventricle depolarization) and B-point (the opening of the aortic valve; e.g., Berntson, Lozano, Chen, & Cacioppo, 2004; Cacioppo et al., 1994; Sherwood et al., 1990). However, the challenge here is that Q-onset is not visible in all people (DeMarzo & Lang, 1996). Furthermore, although some researchers suggested that PEP is the most sensitive measure of beta-adrenergic influence on the heart (e.g., Kelsey, 2012), others claim that virtually all of the sympathetically mediated variation in PEP is captured by RB interval, that is, the interval between R-peak and B-point (Kelsey & Guethlein, 1990; Mezzacappa et al., 1999). Thus, in the current study, we analyze both PEP and RB interval. Nevertheless, the B-point, required for calculating both PEP and RB interval, can be difficult to locate and is prone to signal distortion (see more in the following paragraphs; e.g., Lozano et al., 2007). Thus, it has been proposed that analyzing RZ interval, the interval between R-peak and C-point (the moment corresponding to the maximum blood flow through the aortic valve) is more practical (Lozano et al., 2007). However, although the three measures are closely related, PEP and RB interval are more directly associated with sympathetic activation than RZ interval (Eijnatten et al., 2014; Mezzacappa et al., 1999). We present therefore the analysis of RZ interval in the Supplementary Materials.

INSERT FIGURE 1 ABOUT HERE

Importantly, the abovementioned measures are more sensitive to changes in the sympathetic impact on the heart than popular cardiovascular indices such as blood pressure or heart rate (e.g., Berntson, Quigley, & Lozano, 2007). Systolic blood pressure is influenced not only by the force with which the heart contracts but also by total peripheral resistance, which has a complex relationship with sympathetic activity. Consequently, systolic blood pressure reflects beta-adrenergic sympathetic activity only when parallel changes in total peripheral resistance are very small. The same applies to diastolic blood pressure, which is less influenced by cardiac contractility than by total peripheral resistance. Finally, heart rate is influenced by both parasympathetic and sympathetic outflow. However, as mentioned above, quantifying PEP, or RB, or even RZ interval, can be challenging.

1.2 Challenges in quantifying sympathetic cardiac activity

Impedance cardiograms are prone to distortion of the signal, especially due to motion artifacts (e.g., Cybulski et al., 2007; Cybulski et al., 2018; Hurwitz, Shyu, Reddy, Schneiderman, & Nagel, 1990; Qu, Zhang, Webster, & Tompkins, 1986). Research using Holter recordings has shown that, on average, only about 60% of the signal is artifact-free and, in extreme cases, it can be as low as 20% (Cybulski et al., 2007). One could expect the proportion of artifact-free signal to be much higher in strictly controlled laboratory studies as compared to daytime, portable holter recordings, but there are multiple situations in which, even in the lab, the signal quality can be compromised.

Artifacts can be expected in any study that requires movements such as locomotion, extensive head, neck, or torso movement, as well as even small hand movements. It has been shown that at rest in the supine position, signal quality was almost perfect with a 98% artifact-free signal, whereas during walking, turning over in a supine position, or walking on stairs only 79%, 77%, and 74% of the impedance signals were artifact-free, respectively (Cybulski et al., 2011). Furthermore, a high percentage of artifacts has been observed even for tasks which require little movements: 80% of the signal were artifact-free when sitting and 78% when reading while sitting (Cybulski et al., 2011). Interestingly, tasks requiring participants to speak might cause large distortions in the location of an impedance cardiogram's B-point, which might be even larger than for bicycle exercise (Hurwitz et al., 1990). However, it is also worth noting that in other studies, there were no issues related to ICG measurement during speaking tasks (e.g., Kelsey et al., 1999, 2000, 2004). One could therefore expect that virtually any procedure that requires participants to perform even small movements could introduce some noise in the signal.

It is known that careful placement of the electrodes improves signal quality, but it is insufficient to obtain a completely artifact-free signal (Cybulski et al., 2018). One of the often employed methods of dealing with the imperfect measurement of electrocardiograms and impedance cardiograms is ensemble averaging (Hurwitz et al., 1990; Qu et al., 1986; Zhang et al., 1986). In this method, the impedance cardiogram signal is averaged, beat-by-beat, according to a chosen landmark, usually the R-peak. However, averaging in this way may introduce biases in the signal (e.g., Pandey & Pandey, 2005) and, thus, averaging a very noisy signal from participants who are moving or speaking might result in biased estimates. In some standard settings this might be acceptable as the signal can later be inspected and treated offline. In other cases, however, this would not be adequate. For instance, in some situation, the data from a task period may be extremely noisy, so that the relevant landmarks are not visible. Furthermore, if researchers would like to obtain real-time information about a cardiac sympathetic activity, careful, extensive data cleaning would be precluded. This also applies, for example, to adaptive automation for which dynamic task-control balancing of task requirements is required (e.g., Pope, Bogart, & Bartolome, 1995; Schaefer, Haarmann, & Boucsein, 2008). Thus, the existing methods of dealing with noisy impedance signals are not satisfactory. Fortunately, research on cardiac recovery shows that task-related cardiac activity does not disappear or return to baseline values immediately after a task.

1.3. Residual cardiac activity during recovery

While cardiac reactivity is the magnitude of change in one or more parameters during a performance of a task, cardiac recovery is a response to the termination of a task and usually involves a return to pre-task baseline levels (e.g., Linden, Earle, Gerin, & Christenfeld, 1997). Depending on how challenging a task was and which measure is considered, it may take up to several minutes for the cardiac parameters to return to baseline values (Panaite, Salomon, Jin, & Rottenberg, 2015). It has been shown that within the first minute of recovery after a psychologically stressful task, heart period (the inverse of heart rate) change scores increased by 75% on average (Spalding, Jeffers, Porges, & Hatfield, 2000).

However, recovery dynamics depend on many task-related and individual characteristics. Regarding a task, the most important characteristic seems to be the level of activity while performing it. For example, Pierpont and colleagues (2000) found that HR stabilized around 3 minutes after treadmill exercise. Another factor that influences cardiovascular recovery is task duration, but findings related to its impact have been conflicting (Michael, Graham, & Davis, 2017). Apart from task conditions, cardiac recovery also seems to be sensitive to individual characteristics. The literature suggests fitness, age, ethnicity, and (although with somewhat mixed findings) gender might have an important influence on cardiovascular recovery dynamics (e.g., Carillo et al., 2001; Carter, Watenpaugh & Smith, 2001; Dorr et al., 2007; Forcier et al., 2006; Fichera & Anreassi, 2000; Girdler & Turner, 1990; Hamidovic et al., 2020; Kudielka et al., 2004; Lash et al., 1991; Stoney, Davis & Matthiews, 1987).

Most prior research on cardiovascular recovery has focused on heart rate, heart rate variability, and blood pressure measures. PEP has rarely been examined during recovery (Michael et al., 2017). For example, in a meta-analysis on cardiac recovery and its impact on heart failure and all-cause mortality by Panaite and colleagues (2015), out of 37 included studies, 34 focused on HR, 8 analysed blood pressure recovery patterns, but only one (i.e., Heponiemi et al., 2007) considered PEP. Nevertheless, there are a few studies in which researchers described PEP recovery patterns.

For example, it has been shown that at low levels of task difficulty, the differences between PEP scores in task and recovery periods occur not earlier than 30 seconds post-task and the activity returned to baseline values at the end of a 5-minute recovery period (Nandi & Spodick, 1977). At higher levels of task difficulty, the residual PEP activity did not significantly differ from the task reactivity until much later throughout the 5-minute recovery period and it did not return to baseline values in this period. In contrast, after the first 30 seconds of recovery, HR reactivity differed from task reactivity irrespective of how challenging the task was, and it seemed that HR approached baseline values faster than it was the case for PEP.

In line with these findings, there is evidence that cardiac recovery results mainly from post-challenge vagal reactivation (e.g., Imai et al., 1994; Linden et al., 1997; Perini et al., 1989). This is because the impact of the parasympathetic (vagal) system on the heart is faster than the sympathetic influence. In particular, increased parasympathetic activity causes the initial post-task reduction in HR, whereas sympathetic withdrawal causes a further decrease in HR at later stages of recovery (e.g., Kannankeril, Le, Kadish, & Goldberger, 2004; Pierpont, Stolpman, & Gornick, 2000). Thus, these findings lead us to expect that sympathetically driven cardiac activity will not dissipate immediately after cessation of a task and that it will correlate with activation *during* the task.

1.4. Overview of the studies

To reiterate, the goal of this research was to (1) analyze cardiac sympathetic recovery and (2) examine whether changes in cardiac sympathetic activity in response to a challenge can be predicted using residual cardiac activity during a post-task recovery period. We analyzed data from two studies (total *N* = 181)[1] in which participants performed a task in a VR environment. In both studies, we measured cardiac activity while participants were performing various tasks in the VR environment and during a 2-minute recovery period directly after the tasks. We correlated cardiac activity in the recovery period with activity during task performance. Next, we used recovery scores to predict condition assignment within a task. Finally, we describe the patterns of the return to baseline. In the main text, we present the results for PEP and RB interval. The analyses of RZ interval and HR are presented in Supplementary Materials.

2. Study 1

2.1. Method

2.1.1. Participants

Sixty participants, 59 men and 1 woman aged 19–24 (*M* = 21.58, *SD* = 1.45, with average BMI, *M* = 24.38, *SD* = 1.79) took part in the study. All participants were firefighter trainees in the second year of their education. All of them already had considerable experience in performing in real rescue operations. Participants were recruited at the College of the State Fire Service in Krakow (Poland). One participant was excluded from the dataset due to problems with ECG recording; one additional person was excluded due to a very noisy ICG signal. Thus, the final sample included 58 participants. This research was approved by the Ethical Committee at the Institute of Applied Psychology at Jagiellonian University.

2.1.2. Measures and Equipment

2.1.2.1. Task

Participants were immersed in VR with a stereoscopic head-mounted display using HTC Vive (HTC, New Taipei City, Taiwan; Valve Corporation, Bellevue, Washington). In the rescue challenge

[1] In this paper we use data from a study published elsewhere (Czarnek, Strojny, Strojny, & Richter, 2020) that focuses on testing theoretical predictions related to effort mobilization during a task. In contrast, here we present an exploratory analysis of the cardiac indices of sympathetic activation in the recovery period.

condition, participants were instructed to perform a simulated rescue operation. Their task was to perform a standard rescue procedure (details of the procedure are outlined in the National Firefighting and Rescue System[2]) implemented in VR and to identify critically injured victims of a car crash. For example, participants could check victims' consciousness, airways, breathing, circulation, and identify victims requiring further medical help. There were 6 victims with various injuries; the time limit for executing the rescue procedure was 5 minutes. In the control condition, participants explored a similar VR environment for five minutes; this environment presented part of a small town, including a traffic junction, local administration buildings, and small stores, but there was no car crash or victims and participants did not have a rescue goal.

2.1.2.2. Physiological Acquisition

We obtained participants' ECG and ICG using a BIOPAC MP160 system. For ECG, we used a 3-lead setup with pre-gelled Ag/AgCl spot electrodes in a Lead-II configuration (electrodes were placed on the right and left clavicles and on the lower left abdomen). For ICG, we used eight 8 Ag/AgCl pre-gelled spot electrodes. The upper voltage recording electrodes were placed at the base of the neck; the lower recording electrodes were placed at the level of the xiphoid process at the mid-axillary lines on the left and right sides of the body. The current electrodes were placed 3 cm above (for the neck) and below (for the abdomen) the recording electrodes. The distance between recording electrodes on the neck and the abdomen was approximately 30 cm. Participants' skin was abraded with ELPREP gel before the electrodes were attached. The ECG and ICG signals were sampled at 1000 Hz using a BioNomadix BN-ECG-2 and a BioNomadix-NICO, respectively. Data was stored with AcqKnowledge 5.0 software. All the hardware and software used to obtain physiological data were developed by BIOPAC (BIOPAC Systems, Goleta, CA, USA).

[2] Available at http://www.straz.gov.pl/english/national_firefighting_rescue_system

2.1.3. Procedure

First, participants provided signed consent and answered a set of demographic questions. Next, they were randomly assigned to either the rescue challenge condition or the control condition. Before performing the VR rescue operation task, participants were instructed how to use the HTC Vive controllers, after which they were asked to wear the VR goggles and watch a relaxing movie while sitting for 8 minutes. While participants were watching the movie, we measured their physiological baseline activity. Next, participants were given task instructions and performed the VR rescue operation task for 5 minutes. After the task, participants were asked to stand still for 2 minutes while wearing the VR headset and being immersed in the VR environment. We continued recording ECG and ICG signals throughout the recovery period, after which participants removed the VR goggles and controllers and completed questionnaires that measured their affect and perception of the task. As the main objective of this paper is an analysis of the recovery period, we do not report performance metrics or questionnaire scores. The data for these variables and all further details of the study procedure can be found in Czarnek and colleagues (2020).

2.1.4. Offline Analysis

We bandpass-filtered the ECG (0.5–40 Hz) and ICG signals (0.5–50 Hz, Hurwitz et al., 1993). QRS complexes in the ECG signal were automatically detected with the Pan-Tomkins algorithm (Pan & Tomkins, 1985). In the ICG signals, C-points were automatically detected using an adaptive template-matching method (BIOPAC, 2016) and B-points were identified using the R-C polynomial method (Lozano et al., 2007). Detected Q-onsets, R-peaks, B-points, and C-points were visually inspected and corrected if necessary (i.e., when a landmark deviated from a definition, the landmark's position was adjusted if possible). We manually removed 2% and 3% of the data in the baseline and the recovery period, respectively (both for PEP and RB), whereas in the task period we removed 14% of the PEP and 13% of RB data.

PEP was defined as the interval between Q-onset (ECG) and B-point (ICG); RB interval was defined as the interval between R-peak (ECG) and B-point (ICG). We removed PEP and RB interval values which deviated by more than ±2 SD from the period median score of a participant. In other words, we first calculated median scores per each period, i.e., baseline, task, and recovery for each participant. Next, we removed PEP and RB interval values which deviated by more than ±2 SD from the period median score. Using data with removed outlying values, we calculated baseline, task, and recovery scores. The cardiac baseline scores were calculated as an arithmetic mean of the data collected during the last 5 minutes of the baseline period. Cardiac task scores were calculated as an arithmetic mean of the data collected during the task (which lasted 5 minutes). Cardiac recovery scores has been calculated in two ways, as described below.

For the analysis of the relationship between cardiac sympathetic task reactivity and post-task residual activity, we averaged PEP and RB interval values over 10-second segments and correlated them with the task-related activity. Importantly, the values in the 10-second segments were non-overlapping, i.e., we averaged the values in the recovery period between the 1st and 10th second of the recovery, then between the 11th and 20th second, the 21st and 30th, and so on for the 120-second recovery measurement. This resulted in twenty-four recovery period scores per participant[3]: twelve for PEP and twelve for RB interval. We computed cardiac change scores by subtracting baseline scores from task scores and each segement of the recovery period scores (Llabre et al., 1991).

For the purposes of graphical presentation and visual exploration of the recovery patterns, we used a finer method of data aggregation: We aggregated PEP and RB interval values over 1-second segments of the recovery. For example, if a participant's heart rate exceeded 60 beats per minute, they had more than one PEP and RB interval value per second; in such cases, we averaged these values. The reason for choosing 1-second aggregation granularity was to make the time resolution as high as possible but at the same time to have the same number of cycles per participant so we could plot the data as a time series. Similarly, we aggregated PEP and RB interval values in the task period using 1-

[3] In this analysis, we did not use ensemble averaging because motion artifacts were present in our data and they would have disproportionately influenced the estimates if only a 10-second time window had been used. Although this procedure is popular and efficient, the estimates are very similar to beat-by-beat scoring (e.g., Kelsey & Guethlein, 1990; Muzi et al., 1985).

second segments for the sole purpose of graphical presentation. Next, we calculated change scores by subtracting baseline scores from each segment score.

2.2. Results

Descriptive statistics and intraclass correlation coefficient (ICC; measure of internal consistency) for PEP and RB per condition are presented in Table 1.

INSERT TABLE 1 ABOUT HERE

2.2.1. Relationship between the task and the recovery activity

2.2.2.1. Correlation between task and recovery scores

We ran a series of linear regression models in which we regressed task scores on the recovery scores, one model per each 10-second segment, separately for PEP and RB interval. This resulted in twelve models for PEP and twelve models for RB intervals. A summary of all the linear regression models for PEP is presented in the Supplementary Tables S2a - S2b. We present the relationships between the individuals' task scores and recovery scores for PEP in Figure 2 (the scores are standardized). We found that the PEP recovery scores calculated over each of the 10-second segments were significantly related to the task scores. The effects persisted when we adjusted p-values for multiple comparisons using the Benjamini-Hochberg procedure (Benjamini & Hochberg,1995)[4]. R^2 varied from .33 to .45, and standardized regression (or beta) coefficients ranged from .57 to .67. The beta coefficients inform how many standard deviations a PEP task score changes per each standard deviation increase in the PEP recovery scores. Given that the beta coefficient in a simple linear regression equals the correlation between the variables, a more intuitive interpretation of these values is probably that the correlations were moderately positive. Although the beta coefficients

[4] The effects for this and other analyses did not change when we re-ran the analysis using robust linear regression which suggests that the correlations were not driven by extreme cases.

tended to be nominally larger for the initial segments of the recovery period, as shown in Supplementary Figure S1, they did not differ from each other.

INSERT FIGURE 2 ABOUT HERE

We repeated the analysis for RB intervals. The summary of all the linear regression models is presented in the Supplementary Tables S3a – S3b. The relationships between the individual RB interval task scores and recovery scores are presented in Figure 3. Similarly, as for PEP, we found that the recovery scores calculated over each of the 10-second periods were positively correlated with the task scores. However, when we applied corrections for multiple analyses, this relationship became insignificant (adjusted p = .054) for two segments of the recovery: 81–90 and 91–100 seconds. R^2 varied from .07 to .37. Beta estimates ranged from .26 to .61, suggesting weak to moderate correlations and, as shown in Supplementary Figure S2, the correlations tended to be stronger for the initial segments of the recovery period.

INSERT FIGURE 3 ABOUT HERE

2.2.2.2. Predicting condition assignment using recovery scores

The next step was to predict whether a participant was in the control vs. rescue challenge condition using scores calculated from 10-second segments of the recovery period. To that aim, we ran a series of logistic regression models in which we regressed task condition assignment (control vs. rescue challenge) on the recovery scores, again one model per each 10-second segment, separately for PEP and RB interval. Similarly, the analysis resulted in twelve regression models for PEP and twelve models for RB interval [5].

[5] We also ran a repeated-measures analysis in which we included task scores as well as scores for each 10-second segment of the recovery. This analysis (as well as the associated graphs, which are presented in the Supplementary Table S4 and Figure S3 for Study 1, Table S14 and Figure S12 for Study 2) shows the differences in cardiac reactivity between the conditions. Because the task scores were coded as Time = 0, the coefficient for the condition represents the differences between the control and experimental conditions during the task. Furthermore, this analysis shows the decrease of activity from the task to the recovery period.

For PEP, we were not able to predict the condition assignment using recovery scores (the effect in the first 10-second segment became insignificant after applying a correction for multiple comparisons). For RB interval, interestingly, we found a relationship between the recovery activity and the condition assignment for every 10-second segment between the 1st and 80th second of the recovery but not for any further segment. In other words, we were able to reliably predict task condition assignment solely on the basis of the recovery scores data from any initial eight 10-second segment (or until the 80th second) of the recovery. However, the prediction was most accurate for the first 30 seconds of the recovery: The R^2 in the first 30 seconds of the recovery varied between .35 and .60, while for the segments between the 40th and 90th second of the recovery it varied between .13 and .27.The details of all the logistic regression models are provided in the Supplementary Tables S5a – S6b).

2.2.2. Patterns of the recovery

The time-series of the 1-second segments of PEP and RB interval scores for the control and rescue challenge conditions are plotted in Figure 4, Panel A and Panel B, respectively. Visual inspection of the change scores suggested that the sympathetic activity decreases most in the first 30 seconds of the recovery period, i.e., the PEP and RB interval change scores become *less* negative within that time segment. For PEP, after 30 seconds of a recovery period, the activity approaches the baseline level. For RB interval, the activity below the baseline level is observed until around 50 seconds post-task. Nevertheless, activity below baseline level occurs only for the condition with relatively strong reactivity during the task period, i.e. the rescue challenge condition. For the control condition, for which the activation during the task was not strong, the recovery pattern quickly returned to baseline values.

INSERT FIGURE 4 ABOUT HERE

2.3 Discussion

In this study, we demonstrated the patterns of cardiac sympathetic recovery using PEP and RB interval. We also showed that the residual cardiac activity from the 2-minute post-task recovery was significantly related to task reactivity. This was the case for each 10-second segment of the recovery and both for PEP and for all except two segments for RB interval. For RB interval, the correlations were stronger for the initial 30–40 seconds of the recovery than for the later segments. Both for PEP and RB interval, the task and recovery scores were moderately correlated. Interestingly, predicting task condition assignment using the recovery scores showed that we can estimate the condition assignment at well above chance level using the first 80 seconds of RB interval, but such an estimate would not be reliable if one used PEP scores. As previously stated, R-peak is much easier to identify than Q-onset (e.g., Seery et al., 2016), potentially making RB interval a more reliable measure. Analysis of intra-class correlation (Table 1) showed that RB interval was indeed more reliable than PEP during the task.

Furthermore, our analysis of the patterns of the recovery suggests that recovery from a task challenge depends on the level of activity during the task: A clear pattern of sympathetic withdrawal was visible mainly for participants who were relatively highly activated during the task, i.e., those who were in an rescue challenge condition. This was evident in a linear decrease in activity during the first 30 and 40 seconds of the recovery for PEP and RB interval, respectively.

Nevertheless, the current findings suggest that task scores, both for PEP and RB interval, might be accurately predicted from the recovery score. The analysis for the RZ interval (Supplementary Tables S7a – S8b and Figures S4 – S6) is in line with the findings reported for PEP and RB interval. Specifically, the correlations between task and recovery scores were positive for all 10-second segments and the condition prediction was successful for the first 90 seconds of the recovery. Overall, it seems that cardiac reactivity measured *after* a task might be indicative of sympathetic activation *during* task performance, especially when there is a relatively high level of task activity. To replicate these findings on a larger dataset, we conducted Study 2.

3. Study 2

The design of Study 2 was almost identical to Study 1: We measured participants' cardiac sympathetic activity during the VR rescue challenge task and in the 2-minute recovery period. This time, however, the number of participants was larger and all of them performed a rescue task, but they were presented with four slightly different scenarios.

3.1. Method

3.1.1. Participants

One hundred and twenty-one participants (119 men, 2 women) aged 19–42 (*M* = 24.11, *SD* = 5.72, with an average BMI, *M* = 24.29, *SD* = 2.00) took part in the study. The participants were professional firefighters (*N* = 31) or trainee firefighters (*N* = 90). Participants were recruited at their workplace, i.e., fire brigade units or the College of the State Fire Service in Krakow (Poland). Three people were excluded because of a noisy ICG signal; an additional 11 people were excluded from the PEP analysis because of either difficulty in finding Q-onset in their ECG recordings or B-point in the ICG signal. Thus, for PEP and RB interval we analysed data from 107 and 116 participants, respectively.

3.1.2. Procedure, Measures, and Equipment

The procedure was almost identical as described in Study 1: we used the same VR set-up, ECG and ICG recording equipment, as well as the pre-processing settings (descriptive statistics are provided in Table 2). However, all the participants performed the rescue operation challenge under four conditions (scenarios). The only difference between the four scenarios was the presence of additional bots or items in the VR simulation. In particular, the control condition was the same as the rescue challenge condition in Study 1. The *bystanders* condition featured several, non-interactive bystander bots in close proximity to the car crash. In the *dog* condition, participants saw a dog at a car crash scene; in the *toy* condition, there was a child's toy inside a crashed car. These three conditions differed subtly from the control condition and were not intended to significantly change the users' course of action. The original goal of this study was to assess whether such subtle manipulations could evoke stronger effort mobilization from the rescuers. However, here we use the data from this study to assess the cardiac sympathetic recovery the utility of such data to measure task engagement. We manually removed 12%, 33%, and 16% of the data in the baseline, task, and the recovery period, respectively (both for PEP and RB)

3.2. Results

Descriptive statistics and ICC for PEP and RB are presented in Table 2.

INSERT TABLE 2 ABOUT HERE

3.2.1. Relationship between the task and the recovery activity

3.2.1.1. Correlation between task and recovery scores

We found that the PEP recovery scores calculated over each of the 10-second segments were significantly related to the task scores, even after adjustment for multiple analyses. A summary of these analyses is presented in Supplementary Tables S12a – S12b; the scatter plots presenting the relationship between PEP task scores and recovery scores are displayed in Figure 5. The R^2 varied from .20 to .41. Beta coefficients ranged from .44 to .64, which again suggests a moderate correlation between task and recovery scores; as shown in Supplementary Figure S10, these values did not differ from each other.

INSERT FIGURE 5 ABOUT HERE

Next, we ran the same analysis for RB intervals. Unlike in Study 1, we found that the recovery scores calculated over each of the 10-second periods were not related to the task scores (the correlation from the 11–20-second segment of the recovery became non-significant after adjustment for multiple analysis). A summary of all the models is presented in Supplementary Tables S13a – S13b, the beta coefficients are presented in Supplementary Figure S11, and the relationships between the RB interval task scores and recovery scores is displayed in Figure 6.

INSERT FIGURE 6 ABOUT HERE

3.2.1.2. Predicting condition assignment using recovery scores

We planned to predict condition assignment (control vs. every other task condition) using scores calculated from 10-second segments of the recovery period. However, as significant differences between the conditions during the task performance were observed only for RB interval for the bystanders vs. control condition, we aimed to predict condition assignment only for these two condition (see Supplementary Table S14 and Figure S12, for details). Nevertheless, the prediction of condition assignment was not successful. The details of the analysis are presented in the Supplementary Tables S15a – S16b (for PEP and RB interval).

3.2.2. Recovery patterns

The time series of the averaged 1-second segments of PEP and RB interval scores are shown in Figure 7, Panel A and Panel B, respectively. Similarly to Study 1, visual inspection of the change scores suggests that sympathetic activity decreases greatly after the first 30 seconds of the recovery period but is still below the baseline value until around 60 seconds post task for both indices.

INSERT FIGURE 7 ABOUT HERE

3.3. Discussion

As in Study 1, we found that the PEP scores from the 2-minute recovery were significantly related to the PEP scores during the task. This time, however, the correlation for PEP was higher and more stable across the recovery than it was for RB interval, for which the correlations were, surprisingly, insignificant. Although the correlations for RB interval are insignificant, we found stable correlations between task and recovery scores for RZ interval (Supplementary Tables S16a – S16b and Figures S13 – S14). The correlations for PEP were also slightly lower for Study 2 than for Study 1. Although in Study 2 participants' age and fitness level varied more than in Study 1[6], this is unlikely a reason for more modest correlations than in Study 2. This is because cardiac recovery tend to be slower for the people who are less physically fit (e.g., Darr, Bassett, Morgan, & Thomas, 1988). Furthermore, the predictions of condition assignment using recovery scores were unsuccessful in Study 2 because reactivity during task performance did not differ much across conditions, thus making the prediction task impossible.

The analysis of the recovery patterns confirms the findings from Study 1: we found that both measures, PEP and RB, demonstrated a monotonic drop within the first 30-40 seconds of the recovery. This time the pattern of sympathetic withdrawal was also clear across all the conditions as we observed rather high levels of activity during task performance in the whole sample. The similar recovery pattern was also discovered for RZ interval (Supplementary Figure S15).

4. Conclusions

In the current research, we focused on (1) describing patterns of cardiac sympathetic recovery and (2) examining the usefulness of post-task recovery cardiac activity to determine levels of activity in the preceding task. We showed that sympathetic activity, measured with PEP and RB interval as

[6] The age range in Study 1 was 19 to 24 years, whereas in Study 2 it was 19 to 42 years. Furthermore, we compared the BMI, as a rough estimate of physical fitness, of Study 2 participants: the BMI of the firefighter trainees (M = 23.92, SD = 1.74) was lower in comparison to the BMI of the professional firefighters (M = 25.40, SD = 2.32, Welch t-test: $t(42.20) = -3.24$, CI[-2.40, -0.56], $p = .002$).

well as RZ interval, from the first 20–30 seconds after a task allows assessment of task-related sympathetic activity. In our opinion, the current findings might be especially useful in situations such as intensive movements or locomotion during the task or when researchers need to obtain real-time indices of sympathetic activity.

Our research could also inform studies in which sympathetic activity is assessed several times throughout an experimental session. It should be noted that the length of the between-task interval needs to be adjusted to the intensity of engagement in the preceding task as well as to the aforementioned characteristics of individuals. Given that our sample comprised mostly young and fit men (for whom cardiac recovery is rather fast), the break between the two consecutive tasks should probably not be shorter than 1 minute. Otherwise, researchers could expect the activation from a previous task to impact subsequent measurements, that is, a carry-over effect.

Our findings suggest that task-related sympathetic activity is rather quick and dissipates in well under 1 minute. However, as already mentioned, it is worth highlighting that samples in both Study 1 and Study 2 were relatively homogenous: The vast majority of the participants were male, young, fit, and all were white. As has been shown, characteristics such as age, fitness, or gender might impact cardiac dynamics (e.g., Forcier et al., 2006). Thus, these individual characteristics as well as the intensity of activity while performing a preceding task might be expected to influence recovery. We believe the analysis of these factors in cardiac sympathetic recovery is an important avenue for research in the future.

Summing up, our analysis demonstrated the pattern of sympathetically driven cardiac activity during recovery and suggests that it may serve as a useful indicator of task-related activity. If necessary, although not ideal, it could help in assessing sympathetic activity when such a measurement during a task is not possible.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289-300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Berntson, G. G., Cacioppo, J. T., & Quigley, K. S. (1991). Autonomic determinism: The modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. *Psychological Review*, *98*(4), 459–487. https://doi.org/10.1037/0033-295X.98.4.459

Berntson, G. G., Lozano, D. L., Chen, Y.-J., & Cacioppo, J. T. (2004). Where to Q in PEP. *Psychophysiology*, *41*(2), 333–337. https://doi.org/10.1111/j.1469-8986.2004.00156.x

Berntson, G., Quigley, K. S., & Lozano, D. L. (2007). Cardiovascular psychophysiology. In J. T. Cacioppo & L. G. Tassinary (Eds.), *Handbook of Psychophysiology* (pp. 182–210). Cambridge, UK: Cambridge University Press.

Boutcher, Y. N., & Boutcher, S. H. (2006). Cardiovascular response to Stroop: Effect of verbal response and task difficulty. *Biological Psychology*, *73*(3), 235–241. https://doi.org/10.1016/j.biopsycho.2006.04.005

Brehm, J. W., & Self, E. A. (1989). The Intensity of Motivation. *Annual Review of Psychology*, *40*(1), 109–131. https://doi.org/10.1146/annurev.ps.40.020189.000545

Cacioppo, J. T., Berntson, G., Binkley, P. F., Quigley, K. S., Uchino, B. N., & Fieldstone, A. (1994). Autonomic cardiac control. II. Noninvasive indices and basal response as revealed by autonomic blockades. *Psychophysiology*, *31*(6), 586–598. https://doi.org/10.1111/j.1469-8986.1994.tb02351.x

Carrillo, E., Moya-Albiol, L., González-Bono, E., Salvador, A., Ricarte, J., & Gómez-Amor, J. (2001). Gender differences in cardiovascular and electrodermal responses to public speaking task: the role of anxiety and mood states. *International Journal of Psychophysiology*, *42*(3), 253–264. https://doi.org/10.1016/s0167-8760(01)00147-7

Carter, R., Watenpaugh, D. E., & Smith, M. L. (2001). Selected Contribution: Gender differences in cardiovascular regulation during recovery from exercise. *Journal of Applied Physiology*, *91*(4), 1902–1907. https://doi.org/10.1152/jappl.2001.91.4.1902

Cybulski, G., Młyńczak, G., Żyliński, M., Strasz, A., Gąsiorowska, A., & Niewiadomski, W. (2018). The Quality of Automatic Artifact Identification in Ambulatory Impedance Cardiography Monitoring. In H. Eskola, O. Väisänen, J. Viik, & J. Hyttinen (Eds.), *EMBEC & NBC 2017* (Vol. 65, pp. 165–168). https://doi.org/10.1007/978-981-10-5122-7_42

Cybulski, G., Niewiadomski, W., Aksler, M., Strasz, A., Gąsiorowska, A., Laskowska, D., & Pałko, T. (2011). Identification of the Sources of Artefacts in the Holter-Type Impedance Cardiography Recordings. In Á. Jobbágy (Ed.), *5th European Conference of the International Federation for Medical and Biological Engineering* (Vol. 37, pp. 1272–1274). https://doi.org/10.1007/978-3-642-23508-5_329

Cybulski, G., Niewiadomski, W., Gąsiorowska, A., & Kwiatkowska, D. (2007). Signal quality evaluation in ambulatory impedance cardiography. In *13th International Conference on Electrical Bioimpedance and the 8th Conference on Electrical Impedance Tomography* (pp. 590-592). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-73841-1_152

Czarnek, G., Strojny, P., Strojny, A., & Richter, M. (2020). Assessing engagement during rescue operation simulated in virtual reality: a psychophysiological study. *International Journal of Human–Computer Interaction*, *36* (5), 464-476. https://doi.org/10.1080/10447318.2019.1655905

Darr, K. C., Bassett, D. R., Morgan, B. J., & Thomas, D. P. (1988). Effect of age and training status on heart rate recovery after peak exercise. *American Journal of Physiology-Heart and Circulatory Physiology*, *254*(2), H340–H343. https://doi.org/10.1152/ajpheart.1988.254.2.H340

DeMarzo, A. P., & Lang, R. M. (1996). A new algorithm for improved detection of aortic valve opening by impedance cardiography. *Computers in Cardiology*, 373–376. https://doi.org/10.1109/CIC.1996.542551

Dorr, N., Brosschot, J. F., Sollers, J. J., & Thayer, J. F. (2007). Damned if you do, damned if you dont: The differential effect of expression and inhibition of anger on cardiovascular recovery in Black and White males. *International Journal of Psychophysiology*, *66*(2), 125–134. doi: https://doi.org/10.1016/j.ijpsycho.2007.03.022

Eijnatten, M. A. J. M. van, Rijssel, M. J. van, Peters, R. J. A., Verdaasdonk, R. M., & Meijer, J. H. (2014). Comparison of cardiac time intervals between echocardiography and impedance cardiography at various heart rates. *Journal of Electrical Bioimpedance*, *5*(1), 2–8. https://doi.org/10.5617/jeb.690

Fichera, L., & Andreassi, J. L. (2000). Cardiovascular reactivity during public speaking as a function of personality variables. *International Journal of Psychophysiology*, *37*(3), 267–273. https://doi.org/10.1016/s0167-8760(00)00106-9

Forcier, K., Stroud, L. R., Papandonatos, G. D., Hitsman, B., Reiches, M., Krishnamoorthy, J., & Niaura, R. (2006). Links between physical fitness and cardiovascular reactivity and recovery to psychological stressors: A meta-analysis. *Health Psychology*, *25*(6), 723–739. https://doi.org/10.1037/0278-6133.25.6.723

Girdler, S. S., Turner, J. R., Sherwood, A., & Light, K. C. (1990). Gender differences in blood pressure control during a variety of behavioral stressors. *Psychosomatic Medicine*, *52*(5), 571–591. https://doi.org/10.1097/00006842-199009000-00009

Hamidovic, A., Hedger, K. V., Choi, S. H., Flowers, S., Wardle, M., & Childs, E. (2020). Quantitative meta-analysis of heart rate variability finds reduced parasympathetic cardiac tone in women compared to men during laboratory-based social stress. *Neuroscience & Biobehavioral Reviews*, *114*, 194–200. https://doi.org/10.1016/j.neubiorev.2020.04.005

Heponiemi, T., Elovainio, M., Pulkki, L., Puttonen, S., Raitakari, O., & Keltikangas-Järvinen, L. (2007). Cardiac autonomic reactivity and recovery in predicting carotid atherosclerosis: The cardiovascular risk in young Finns study. *Health Psychology*, *26*(1), 13–21. https://doi.org/10.1037/0278-6133.26.1.13

Hurwitz, B. E., Shyu, L. Y., Lu, C. C., Reddy, S. P., Schneiderman, N., & Nagel, J. H. (1993). Signal fidelity requirements for deriving impedance cardiography measures of cardiac function over a broad heart rate range. *Biological Psychology*, *36*(1-2), 3-21. https://doi.org/10.1016/0301-0511(93)90076-K

Hurwitz, B. E., Shyu, L.-Y., Reddy, S. P., Schneiderman, N., & Nagel, J. H. (1990). Coherent ensemble averaging techniques for impedance cardiography. *Proceedings. Third Annual IEEE Symposium on Computer-Based Medical Systems*, 228–235. https://doi.org/10.1109/CBMSYS.1990.109403

Imai, K., Sato, H., Hori, M., Kusuoka, H., Ozaki, H., Yokoyama, H., … Kamada, T. (1994). Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. *Journal of the American College of Cardiology*, *24*(6), 1529–1535. https://doi.org/10.1016/0735-1097(94)90150-3

Jones, P. P., Spraul, M., Matt, K. S., Seals, D. R., Skinner, J. S., & Ravussin, E. (1996). Gender does not influence sympathetic neural reactivity to stress in healthy humans. *American Journal of Physiology-Heart and Circulatory Physiology*, *270*(1). https://doi.org/10.1152/ajpheart.1996.270.1.h350

Kannankeril, P. J., Le, F. K., Kadish, A. H., & Goldberger, J. J. (2004). Parasympathetic Effects on Heart Rate Recovery after Exercise. *Journal of Investigative Medicine*, *52*(6), 394–401. https://doi.org/10.1136/jim-52-06-34

Kelsey, R. M. (2012). Beta-adrenergic cardiovascular reactivity and adaptation to stress: The cardiac pre-ejection period as an index of effort. In R. A. Wright & G. H. E. Gendolla (Eds.), *How* *motivation affects cardiovascular response: Mechanisms and applications.* (pp. 43–60). https://doi.org/10.1037/13090-002

Kelsey, R. M., Blascovich, J., Tomaka, J., Leitten, C. L., Schneider, T. R., & Wiens, S. (1999). Cardiovascular reactivity and adaptation to recurrent psychological stress: Effects of prior task exposure. Psychophysiology, 36, 818–831. https://doi.org/10.1111/1469-8986.3660818

Kelsey, R. M., Blascovich, J., Leitten, C. L., Schneider, T. R., Tomaka, J., & Wiens, S. (2000). Cardiovascular reactivity and adaptation to recurrent psychological stress: The moderating effects of evaluative observation. Psychophysiology, 37, 748–756. https://doi.org/10.1111/1469-8986.3760748

Kelsey, R. M., & Guethlein, W. (1990). An evaluation of the ensemble averaged impedance cardiogram. *Psychophysiology*, *27*(1), 24-33. https://doi.org/10.1111/j.1469-8986.1990.tb02173.x.

Kelsey, R. M., Soderlund, K., & Arthur, C. M. (2004). Cardiovascular reactivity and adaptation to recurrent psychological stress: Replication and extension. Psychophysiology, 41, 924–934. https://doi.org/10.1111/j.1469-8986.2004.00245.x

Kelsey, R. M., Reiff, S., Wiens, S., Schneider, T. R., Mezzacappa, E. S., & Guethlein, W. (1998). The ensemble averaged impedance cardiogram: An evaluation of scoring methods and interrater reliability. Psychophysiology, 35, 337–340. https://doi.org/10.1017/S0048577298001310

Kudielka, B. M., Buske-Kirschbaum, A., Hellhammer, D. H., & Kirschbaum, C. (2004). Differential heart rate reactivity and recovery after psychosocial stress (TSST) in healthy children, younger adults, and elderly adults: The impact of age and gender. *International Journal of Behavioral Medicine*, *11*(2), 116–121. https://doi.org/10.1207/s15327558ijbm1102_8

Lash, S. J., Gillespie, B. L., Eisler, R. M., & Southard, D. R. (1991). Sex differences in cardiovascular reactivity: Effects of the gender relevance of the stressor. *Health Psychology*, *10*(6), 392–398. https://doi.org/10.1037/0278-6133.10.6.392

Linden, W., Earle, T. L., Gerin, W., & Christenfeld, N. (1997). Physiological stress reactivity and recovery: Conceptual siblings separated at birth? *Journal of Psychosomatic Research*, *42*(2), 117–135. https://doi.org/10.1016/S0022-3999(96)00240-1

Lozano, D. L., Norman, G., Knox, D., Wood, B. L., Miller, B. D., Emery, C. F., & Berntson, G. G. (2007). Where to B in dZ/dt. *Psychophysiology*, *44*(1), 113–119. https://doi.org/10.1111/j.1469-8986.2006.00468.x

Mezzacappa, E. S., Kelsey, R. M., & Katkin, E. S. (1999). The effects of epinephrine administration on impedance cardiographic measures of cardiovascular function. *International Journal of Psychophysiology*, *31*(3), 189–196. https://doi.org/10.1016/S0167-8760(98)00058-0

Michael, S. F., Graham, K. S., & Davis, G. M. (2017). Cardiac Autonomic Responses during Exercise and Post-exercise Recovery Using Heart Rate Variability and Systolic Time Intervals—A Review. *Frontiers in Physiology*, *8*, 301. https://doi.org/10.3389/fphys.2017.00301

Muzi, M., Ebert, T. J., Tristani, F. E., Jeutter, D. C., Barney, J. A., & Smith, J. J. (1985). Determination of cardiac output using ensemble-averaged impedance cardiograms. *Journal of Applied Physiology*, *58*(1), 200-205. https://doi.org/10.1152/jappl.1985.58.1.200.

Nandi, P. S., & Spodick, D. H. (1977). Recovery from exercise at varying workloads. Time course of responses of heart rate and systolic intervals. *Heart*, *39*(9), 958–966. https://doi.org/10.1136/hrt.39.9.958

Obrist, P. A. (1976). The cardiovascular-behavioral interaction—As it appears today. *Psychophysiology*, *13*(2), 95–107. https://doi.org/10.1111/j.1469-8986.1976.tb00081.x.

Obrist, P. A. (1981). *Cardiovascular psychophysiology: A perspective.* New York, NY: Plenum Press. https://doi.org/10.1017/S0033291700043671

Panaite, V., Salomon, K., Jin, A., & Rottenberg, J. (2015). Cardiovascular Recovery from Psychological and Physiological Challenge and Risk for Adverse Cardiovascular Outcomes and All-Cause Mortality: *Psychosomatic Medicine*, *77*(3), 215–226. https://doi.org/10.1097/PSY.0000000000000171

Pandey, V. K., & Pandey, P. C. (2005). Cancellation of Respiratory Artifact in Impedance Cardiography. *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, 5503–5506. https://doi.org/10.1109/IEMBS.2005.1615729

Perini, R., Orizio, C., Comandè, A., Castellano, M., Beschi, M., & Veicsteinas, A. (1989). Plasma norepinephrine and heart rate dynamics during recovery from submaximal exercise in man. *European Journal of Applied Physiology and Occupational Physiology*, *58*(8), 879–883. https://doi.org/10.1007/BF02332222

Pierpont, G. L., Stolpman, D. R., & Gornick, C. C. (2000). Heart rate recovery post-exercise as an index of parasympathetic activity. *Journal of the Autonomic Nervous System*, *80*(3), 169–174. https://doi.org/10.1016/S0165-1838(00)00090-4

Pope, A. T., Bogart, E. H., & Bartolome, D. S. (1995). Biocybernetic system evaluates indices of operator engagement in automated task. *Biological Psychology*, *40*(1–2), 187–195. https://doi.org/10.1016/0301-0511(95)05116-3

Qu, M., Zhang, Y., Webster, J. G., & Tompkins, W. J. (1986). Motion Artifact from Spot and Band Electrodes During Impedance Cardiography. *IEEE Transactions on Biomedical Engineering*, *BME-33*(11), 1029–1036. https://doi.org/10.1109/TBME.1986.325869

Roger, D., & Jamieson, J. (1988). Individual differences in delayed heart-rate recovery following stress: The role of extraversion, neuroticism and emotional control. *Personality and Individual Differences*, *9*(4), 721–726. https://doi.org/10.1016/0191-8869(88)90061-x

Rowell, L. B. (1993). *Human Cardiovascular Control*. New York, NY: Oxford University Press. https://doi.org/10.1002/clc.4960170212.

Schaefer, F., Haarmann, A., & Boucsein, W. (2008). The Usability of Cardiovascular and Electrodermal Measures for Adaptive Automation. In J. H. D. M. Westerink, M. Ouwerkerk, T. J. M. Overbeek, W. F. Pasveer, & B. de Ruyter (Eds.), *Probing Experience* (Vol. 8, pp. 235–243). https://doi.org/10.1007/978-1-4020-6593-4_20

Seery, M. D., Kondrak, C. L., Streamer, L., Saltsman, T. L., & Lamarche, V. M. (2016). Pre-ejection period can be calculated using R peak instead of Q. *Psychophysiology*, *53*, 1232–1240. https://doi.org/10.1111/psyp.12657

Sherwood, A., Allen, M. T., Fahrenberg, J., Kelsey, R. M., Lovallo, W. R., & Doornen, L. J. P. (1990). Methodological Guidelines for Impedance Cardiography. *Psychophysiology*, *27*(1), 1–23. https://doi.org/10.1111/j.1469-8986.1990.tb02171.x

Spalding, T. W., Jeffers, L. S., Porges, S. W., & Hatfield, B. D. (2000). Vagal and cardiac reactivity to psychological stressors in trained and untrained men. *Medicine & Science in Sports & Exercise*, *32*(3), 581–591. https://doi.org/10.1097/00005768-200003000-00006.

Stoney, C. M., Davis, M. C., & Matthews, K. A. (1987). Sex Differences in Physiological Responses to Stress and in Coronary Heart Disease: A Causal Link? *Psychophysiology*, *24*(2), 127–131. https://doi.org/10.1111/j.1469-8986.1987.tb00264.x

Zhang, Y., Qu, M., Webster, J. G., Tompkins, W. J., Ward, B. A., & Bassett, D. R. (1986). Cardiac Output Monitoring by Impedance Cardiography During Treadmill Exercise. *IEEE Transactions on Biomedical Engineering*, *11*, 1037-1042. https://doi.org/10.1109/TBME.1986.325870.

Authors' note

This work was co-financed under *Widespread Disaster Simulator – research and preparation for implementation* (the Smart Growth Operational Programme, sub-measure 1.1.1. Industrial research and development work implemented by enterprises) received by Nano Games sp. z o.o.

The authors declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

This research was accepted by the Ethical Committee at the Institute of Applied Psychology at Jagiellonian University.

We would like to thank Natalia Dużmańska for her help in data curation.

Tables

Table1

Descriptive statistics and ICC in Study 1

		PEP			RB		
		M	*SD*	*ICC*	*M*	*SD*	*ICC*
Baseline	Control	122.40	12.21	.91	79.64	4.86	.83
	Rescue challenge	121.74	11.70	.77	79.56	4.73	.77
Task	Control	122.15	13.03	.51	77.83	6.84	.70
	Rescue challenge	117.77	14.81	.44	72.49	8.79	.65
Recovery	Control	122.99	10.59	.60	81.07	4.81	.79
	Rescue challenge	121.79	13.70	.77	79.00	5.49	.66

Note. PEP and RB are in ms.

Table2

Descriptive statistics and ICC in Study 2

	PEP			RB		
	M	*SD*	*ICC*	*M*	*SD*	*ICC*
Baseline	122.91	13.99	.87	8.02	5.06	.83
Task	117.05	15.03	.64	72.30	7.86	.70
Recovery	119.3	12.06	.74	78.58	5.69	.70

Note. PEP and RB are in ms.

Figure captions

Figure 1. Non-averaged electrogradiogram (ECG) and impedance cardiogram (ICG; in the form of dZ/dt) with annotated landmarks used to calculate indices of cardiac sympathetic activity.

Figure 2. The relationship between PEP reactivity in a task and 10-second segments of a recovery period (Study 1). The values in parentheses represent the standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

Figure 3. The relationship between RB reactivity in a task and 10-second segments of a recovery period (Study 1). The values in parentheses represent standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

Figure 4. Average change scores for PEP (Panel A) and RB interval (Panel B) in the control and experimental conditions across task and recovery periods (Study 1). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.

Figure 5. The relationship between PEP reactivity in a task and 10-second segments of a recovery period (Study 2). The values in parentheses represent the standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

Figure 6. The relationship between RB interval reactivity in a task and 10-second segments of a recovery period (Study 2). The values in parentheses represent the standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

Figure 7. Average change scores for PEP (Panel A) and RB interval (Panel B) across task and recovery periods (Study 2). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.

Supplementary materials for

Cardiac Sympathetic Activity During Recovery as an Indicator of Sympathetic Activity during Task Performance

Gabriela Czarnek[1,2], Michael Richter[3], Paweł Strojny[1,4]

[1] Nano Games, Cracow (Poland)
[2] Institute of Psychology at Jagiellonian University, Krakow (Poland)
[3] School of Natural Sciences and Psychology at Liverpool John Moores University, Liverpool (UK)
[4] Faculty of Management and Social Communication at Jagiellonian University, Krakow (Poland)

Correspondence concerning this article should be addressed to Gabriela Czarnek, gabriela.czarnek@uj.edu.pl, Ingardena 6, 31-006 Kraków, Poland.

Contents

List of tables and figures

A. Details of Study 1

B. Details of Study 2

Study 1

Table S1

Descriptive statistics and ICC for all the physiological measures in Study 1

Period	Condition	PEP			RB			RZ			HR		
		M	*SD*	*ICC*	*M*	*SD*	*ICC*	*M*	*SD*	*ICC*	*M*	*SD*	*ICC*
Baseline	Control	122.40	12.21	.91	79.64	4.86	.83	146.41	16.14	.81	69.55	9.32	.75
	Rescue challenge	121.74	11.70	.77	79.56	4.73	.77	146.86	17.73	.81	67.04	11.27	.85
Task	Control	122.15	13.03	.51	77.83	6.84	.70	141.99	19.19	.67	75.44	9.32	.70
	Rescue challenge	117.77	14.81	.44	72.49	8.79	.65	127.82	22.83	.60	76.66	12.85	.55
Recovery	Control	122.99	10.59	.60	81.07	4.81	.79	152.05	17.60	.77	77.53	1.77	.74
	Rescue challenge	121.79	13.70	.77	79.00	5.49	.66	145.18	19.12	.71	74.62	14.40	.81

Note. PEP, RB, and RZ are in ms, HR is in beats per minute (bpm).

Correlation between task and recovery scores: summary of the linear regression models

PEP

Table S2a

Summary of regression models of PEP task scores being predicted from 10-second segments of recovery in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.10	1.000	0.00	0.10	1.000	-0.00	0.11	1.000	-0.00	0.10	1.000	0.00	0.11	1.000	-0.00	0.10	1.000
PEP 10-sec recovery	0.67	0.10	**<.001**	0.66	0.10	**<.001**	0.61	0.11	**<.001**	0.67	0.10	**<.001**	0.59	0.11	**<.001**	0.64	0.10	**<.001**
Adjusted p			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**
Observations	56			56			56			56			56			57		
R^2 / R^2 adjusted	.445 / .435			.440 / .430			.372 / .361			.445 / .435			.353 / .341			.416 / .405		

Table S2b

Summary of regression models of PEP task scores being predicted from 10-second segments of recovery in Study 1 (continuation)

	61-70 s			71-80 s			81-90 s			91-100 s			101-110 s			111-120 s		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.11	1.000	-0.00	0.11	1.000	0.00	0.11	1.000	-0.00	0.11	1.000	0.00	0.11	1.000	0.00	0.10	1.000
PEP 10-sec recovery	0.61	0.11	**<.001**	0.63	0.11	**<.001**	0.57	0.11	**<.001**	0.60	0.11	**<.001**	0.60	0.11	**<.001**	0.63	0.10	**<.001**
Adjusted p			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**
Observations	57			56			55			57			58			58		
R^2 / R^2 adjusted	.369 / .358			.393 / .382			.329 / .316			.354 / .343			.356 / .344			.392 / .382		

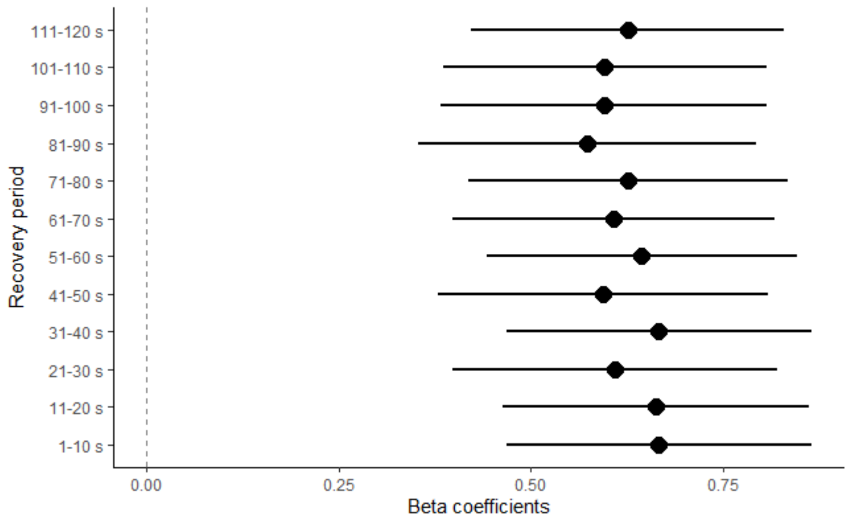


Figure S1. The beta coefficients from the regression analysis for PEP (Study 1). The error bars represent 95% confidence intervals.

RB

Table S3a

Summary of regression models of RB interval task scores being predicted from 10-second segments of recovery in Study 1

	1-10 s			11-20 s			21-30 s			31-40 s			41-50 s			51-60 s		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.	0.11	1.000	-0.	0.11	1.000	-0.	0.12	1.000	-0.	0.11	1.000	-0.	0.12	1.000	-0.	0.12	1.000

	00			00			00			00			00			00		
RB 10-sec recovery	0.59	0.11	**<.001**	0.54	0.11	**<.001**	0.48	0.12	**<.001**	0.61	0.11	**<.001**	0.46	0.12	**<.001**	0.46	0.12	**<.001**
Adjusted p			**<.001**			**<.001**			**<.001**			**<.001**			**.001**			**.001**
Observations	53			56			56			56			56			57		
R^2 / R^2 adjusted	0.344 / 0.331			0.293 / 0.280			0.231 / 0.217			0.372 / 0.360			0.208 / 0.194			0.212 / 0.198		

Table S3b
Summary of regression models of RB interval task scores being predicted from 10-second segments of recovery in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.12	1.000	0.00	0.12	1.000	0.00	0.13	1.000	0.00	0.13	1.000	-0.00	0.13	1.000	-0.00	0.13	1.000
RB 10-sec recovery	0.50	0.12	**<.001**	0.43	0.12	**.001**	0.26	0.13	.054	0.26	0.13	0.053	0.30	0.13	**.023**	0.31	0.13	**.017**
Adjusted p			**<.001**			**.002**			.054			0.054			**.028**			**.023**
Observations	57			56			55			57			58			58		
R^2 / R^2 adjusted	.253 / .239			.181 / .166			.068 / .051			.066 / .049			.089 / .073			.097 / .081		

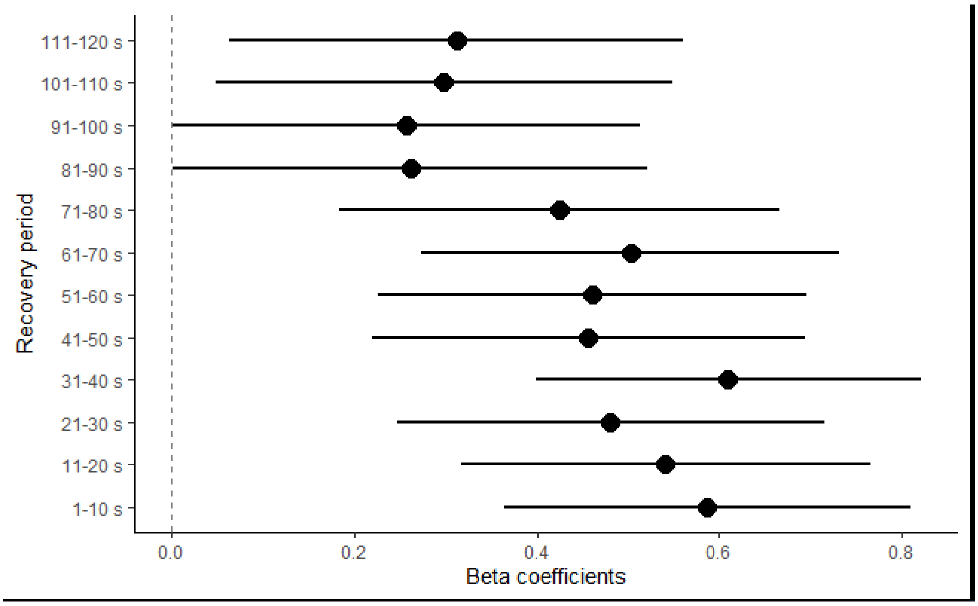


Figure S2. The beta coefficients from the regression analysis for RB interval (Study 1). The error bars represent 95% confidence intervals.

Summary of the repeated-measures models

Table S4
Summary of the repeated-measures models (Study 1)

	PEP			RB			RZ			HR		
Predictors	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*
(Intercept)	-3.80	1.41	**.007**	-4.87	0.39	**<.001**	-14.46	1.26	**<.001**	6.64	0.93	**<.001**
Condition	3.57	1.99	.072	5.00	0.54	**<.001**	15.38	1.77	**<.001**	-1.46	1.32	.269
Time	0.50	0.05	**<.001**	0.60	0.03	**<.001**	1.89	0.09	**<.001**	0.22	0.06	**<.001**
Condition * Time	-0.42	0.07	**<.001**	-0.45	0.04	**<.001**	-1.27	0.12	**<.001**	0.26	0.08	**.001**
Random Effects												
σ^2	11.76			4.41			34.12			14.33		
τ_{00}	53.89 $_{id}$			2.95 $_{id}$			35.33 $_{id}$			21.12 $_{id}$		
N	58 $_{id}$			58 $_{id}$			58 $_{id}$			58 $_{id}$		
Observations	678			675			679			696		
Marginal R^2 / Conditional R^2	.030 / .826			.351 / .611			.378 / .694			.047 / .615		

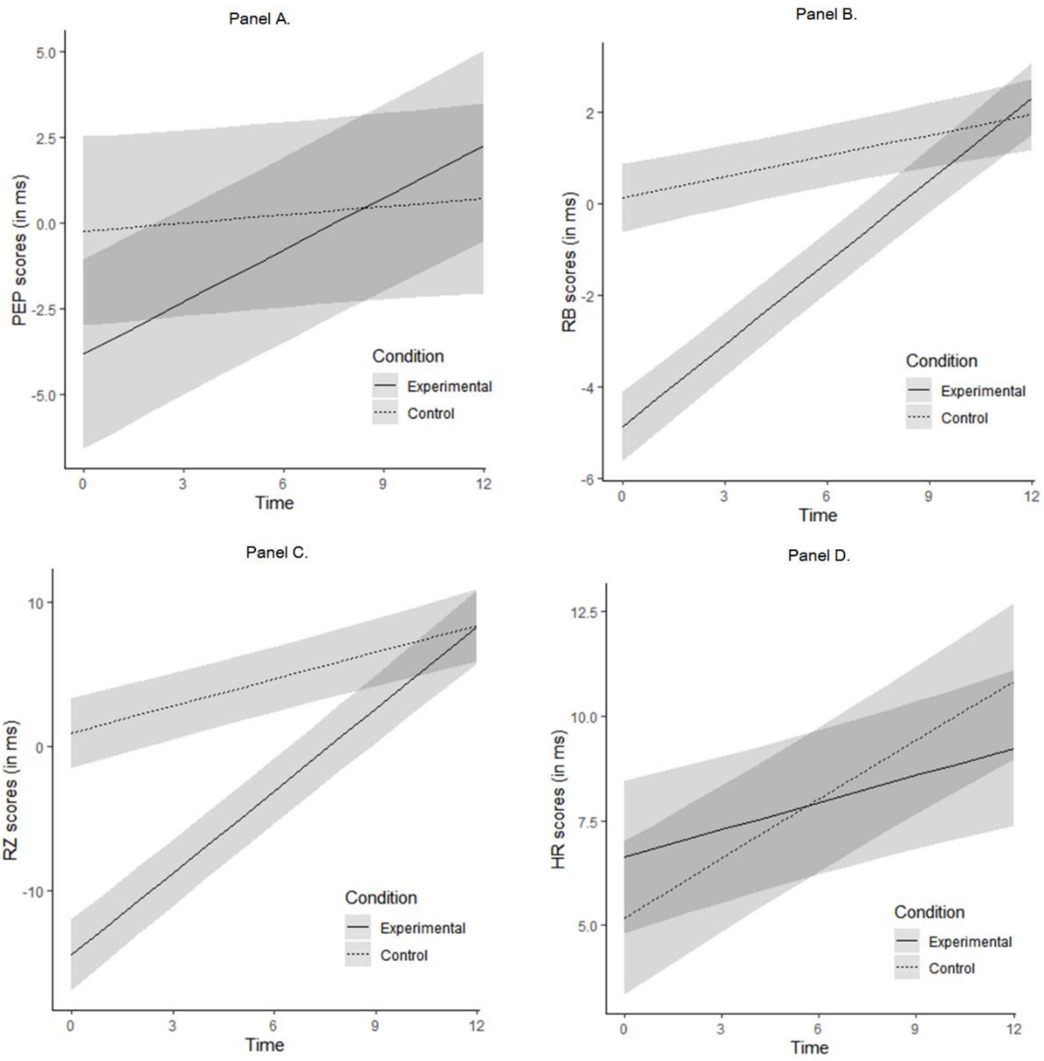


Figure S3. Predicted scores for the repeated measures analysis for PEP (Panel A), RB (Panel B), RZ (Panel C), and HR (Panel D) in Study 1. Grey shaded areas represent 95% confidence intervals.

Predicting condition assignment using recovery data: summary of the logistic regression models

PEP

Table S5a

Summary of the logistic regression models predicting task condition using PEP recovery scores from 10-second segments in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	1.15	0.29	.620	1.18	0.28	.553	1.11	0.27	.709	1.09	0.27	.759	1.07	0.27	.804	1.03	0.27	.910
PEP 10-sec recove	1.10	0.04	**.026**	1.05	0.04	.189	1.02	0.03	.506	1.02	0.03	.600	0.99	0.03	.803	1.01	0.03	.689

ry																		
Adjusted p			.135			.999			.999			.999			.999			.999
Observations	56			56			56			56			56			57		
R^2 Tjur	.119			.039			.008			.005			.001			.003		

Table S5b

Summary of the logistic regression models predicting task condition using PEP recovery scores from 10-second segments in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	1.04	0.27	.895	1.07	0.27	.807	1.01	0.27	.962	0.96	0.27	.884	1.00	0.26	.997	1.00	0.26	.990
PEP 10-sec recovery	1.00	0.03	.999	1.01	0.03	.847	1.02	0.04	.607	1.00	0.03	.928	1.00	0.03	.959	0.99	0.03	.780
Adjusted p			.999			.999			.999			.999			.999			.999
Observations	57			56			55			57			58			58		
R^2 Tjur	.000			.001			.005			.000			.000			.001		

RB

Table S6a

Summary of the logistic regression models predicting task condition using RB interval recovery scores from 10-second segments in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	2.49	0.41	**0.026**	4.58	0.58	**.009**	1.36	0.34	0.372	1.22	0.33	0.550	0.94	0.31	0.852	0.73	0.32	0.320
RB 10-sec recovery	1.98	0.20	**.001**	3.26	0.31	**<.001**	1.93	0.18	**<.001**	1.99	0.20	**.001**	1.72	0.17	**.001**	1.57	0.16	**.004**
			.002			**.002**			**.002**			**.002**			**.003**			**.008**

Observations	53	56	56	56	56	57
R^2 Tjur	.412	.600	.378	.350	.265	.190

Table S6b
Summary of the logistic regression models predicting task condition using RB interval recovery scores from 10-second segments in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	0.79	0.30	.428	0.71	0.33	.302	0.84	0.31	.579	0.99	0.29	.965	0.84	0.30	.574	0.88	0.29	.671
RB 10-sec recovery	1.42	0.15	**.017**	1.52	0.17	**.015**	1.29	0.14	.065	0.98	0.10	.833	1.18	0.13	.212	1.15	0.12	.274
			.026			**.026**			.087			.833			.254			.299
Observations	57			56			55			57			58			58		
R^2 Tjur	.116			.125			.076			.001			.034			.024		

Analysis for RZ interval

We manually removed 1%, 8%, and 1% of the data in the baseline, task, and the recovery period, respectively for RZ interval in Study 1.

Relationship between task and recovery scores for RZ interval

Table S7a
Summary of regression models of RZ interval task scores being predicted from 10-second segments of recovery in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.10	1.000	0.00	0.11	1.000	0.00	0.10	1.000	0.00	0.10	1.000	0.00	0.11	1.000	-0.00	0.11	1.000
RZ 10-sec recovery	0.64	0.11	**<.001**	0.59	0.11	**<.001**	0.63	0.11	**<.001**	0.70	0.10	**<.001**	0.59	0.11	**<.001**	0.57	0.11	**<.001**
Adjuste			**<.0**			**<.0**			**<.0**			**<.0**			**<.0**			**<.0**

d p	**01**	**01**	**01**	**01**	**01**	**01**
Observations	55	56	56	56	57	57
R^2 / R^2 adjusted	.414 / .403	.347 / .335	.398 / .387	.494 / .484	.345 / .333	.319 / .307

Table S7b

Summary of regression models of RZ interval task scores being predicted from 10-second segments of recovery in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.11	1.000	0.00	0.11	1.000	0.00	0.13	1.000	0.00	0.12	1.000	-0.00	0.11	1.000	-0.00	0.12	1.000
RZ 10-sec recovery	0.60	0.11	**<.001**	0.52	0.12	**<.001**	0.36	0.13	**.007**	0.38	0.12	**.004**	0.52	0.11	**<.001**	0.42	0.12	**.001**
Adjusted p			**<.001**			**<.001**			**.007**			**.004**			**<.001**			**.001**
Observations	57			56			56			57			58			58		
R^2 / R^2 adjusted	.359 / .347			.275 / .261			.127 / .111			.142 / .126			.266 / .252			.180 / .165		

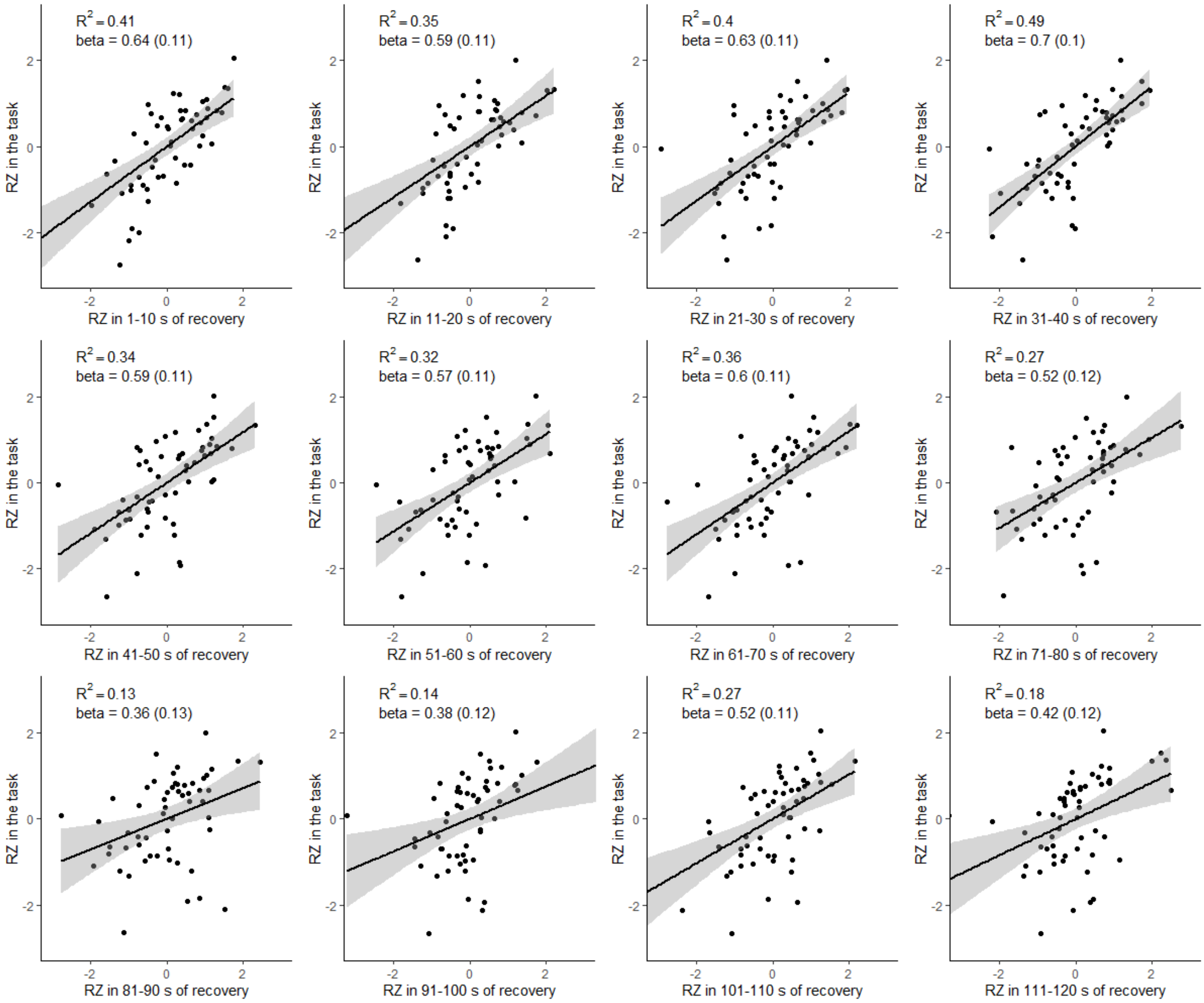


Figure S4. The relationship between RZ interval reactivity in a task and 10-second segments of a recovery period (Study 1). The values in parentheses represent standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

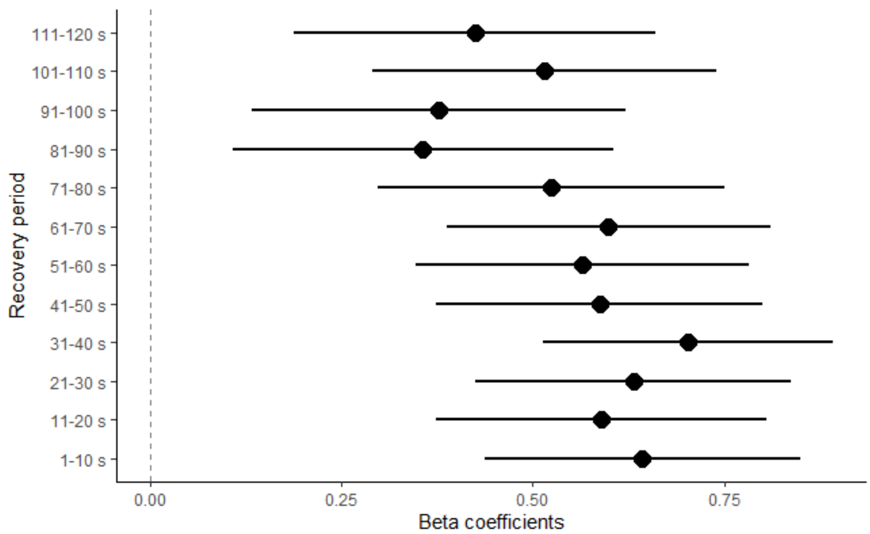


Figure S5. The beta coeffients from the regression analysis for RZ interval (Study 1). The error bars represent 95% confidence intervals.

Predicting task assignment for RZ interval

Table S8a

Summary of the logistic regression models predicting task condition using RZ interval recovery scores from 10-second segments in Study 1

	1-10 s			11-20 s			21-30 s			31-40 s			41-50 s			51-60 s		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	5.24	0.57	**.004**	3.93	0.55	**0.013**	1.33	0.37	0.438	1.17	0.33	0.622	0.78	0.32	0.440	0.68	0.33	0.242
RZ 10-sec recovery	1.31	0.07	**<.001**	1.37	0.08	**<.001**	1.25	0.06	**<.001**	1.19	0.05	**<.001**	1.18	0.05	**.001**	1.14	0.04	**.003**
Adjusted p			**.001**			**.001**			**.001**			**.001**			**.002**			**.006**
Observations	55			56			56			56			57			57		
R^2 Tjur	.526			.577			.442			.335			.263			.196		

Table S8b

Summary of the logistic regression models predicting task condition using RZ interval recovery scores from 10-second segments in Study 1 (continuation)

	61-70 s			71-80 s			81-90 s			91-100 s			101-110 s			111-120 s		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	0.78	0.31	0.417	0.62	0.35	0.177	0.66	0.34	0.226	0.91	0.31	0.747	0.72	0.33	0.318	0.81	0.31	0.483
RZ 10-sec recovery	1.08	0.04	**.033**	1.14	0.05	**.008**	1.10	0.04	**.029**	1.01	0.03	.683	1.08	0.04	.063	1.05	0.03	.159
Adjusted p			**.044**			**.014**			**.044**			.683			.076			.173
Observations	57			56			56			57			58			58		
R^2 Tjur	.092			.142			.099			.003			.071			.038		

Patterns of recovery for RZ interval

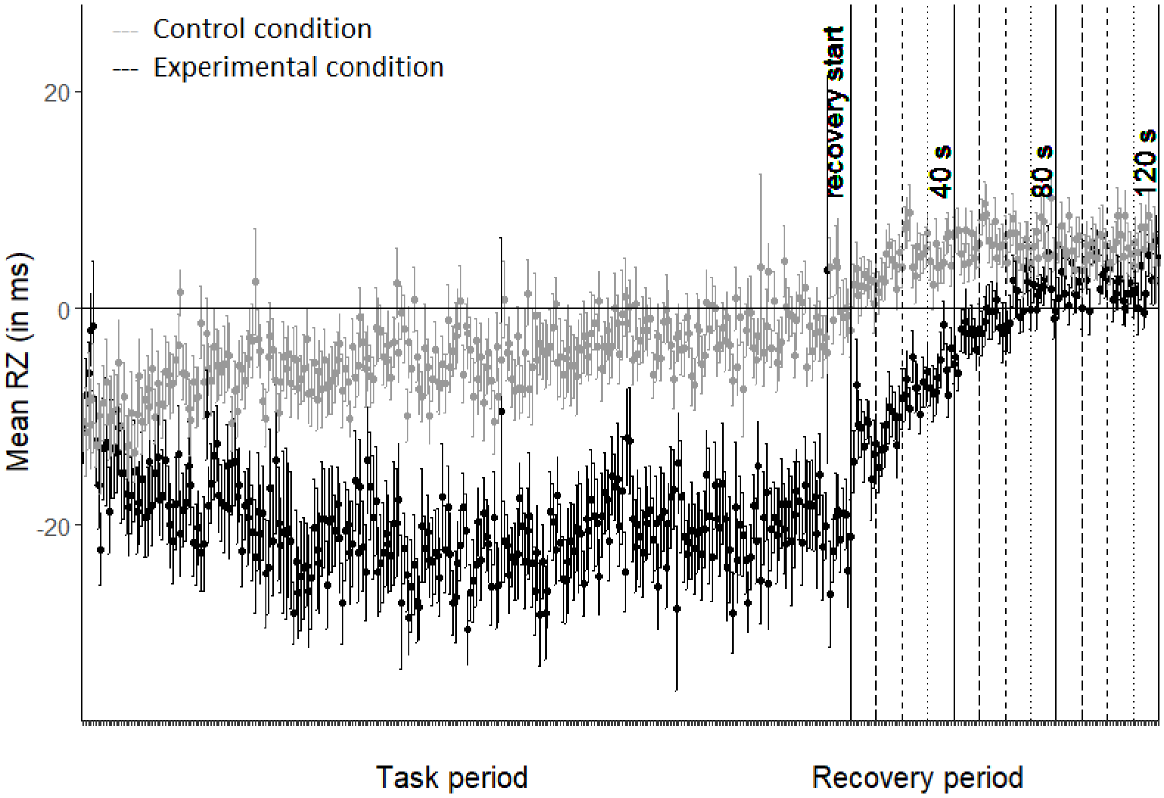


Figure S6. Average change scores of RZ interval in the control and experimental conditions across task and recovery periods (Study 1). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.

Analysis for HR

Relationship between task and recovery scores for HR

Table S9a

Summary of regression models of HR task scores being predicted from 10-second segments of recovery in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.13	1.000	-0.00	0.13	1.000	0.00	0.13	1.000	0.00	0.13	1.000	-0.00	0.13	1.000	0.00	0.13	1.000
HR 10-sec recovery	0.29	0.13	**.026**	0.21	0.13	.112	0.21	0.13	.113	0.18	0.13	.181	0.18	0.13	.171	0.20	0.13	.140
Adjusted p			.307			.309			.309			.309			.309			.309
Observations	58			58			58			58			58			58		
R^2 / R^2 adjusted	.086 / .070			.044 / .027			.044 / .027			.032 / .014			.033 / .016			.039 / .021		

Table S9b

Summary of regression models of HR task scores being predicted from 10-second segments of recovery in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.13	1.000	0.00	0.13	1.000	0.00	0.13	1.000	0.00	0.13	1.000	0.00	0.13	1.000	0.00	0.13	1.000
HR 10-sec recovery	0.17	0.13	.208	0.02	0.13	.893	0.09	0.13	.500	0.14	0.13	.282	0.19	0.13	.155	0.16	0.13	.232
Adjusted p			.309			.893			.546			.339			.309			.309
Observations	58			58			58			58			58			58		
R^2 / R^2 adjusted	.028 / .011			.000 / -.018			.008 / -.010			.021 / .003			.036 / .019			.025 / .008		

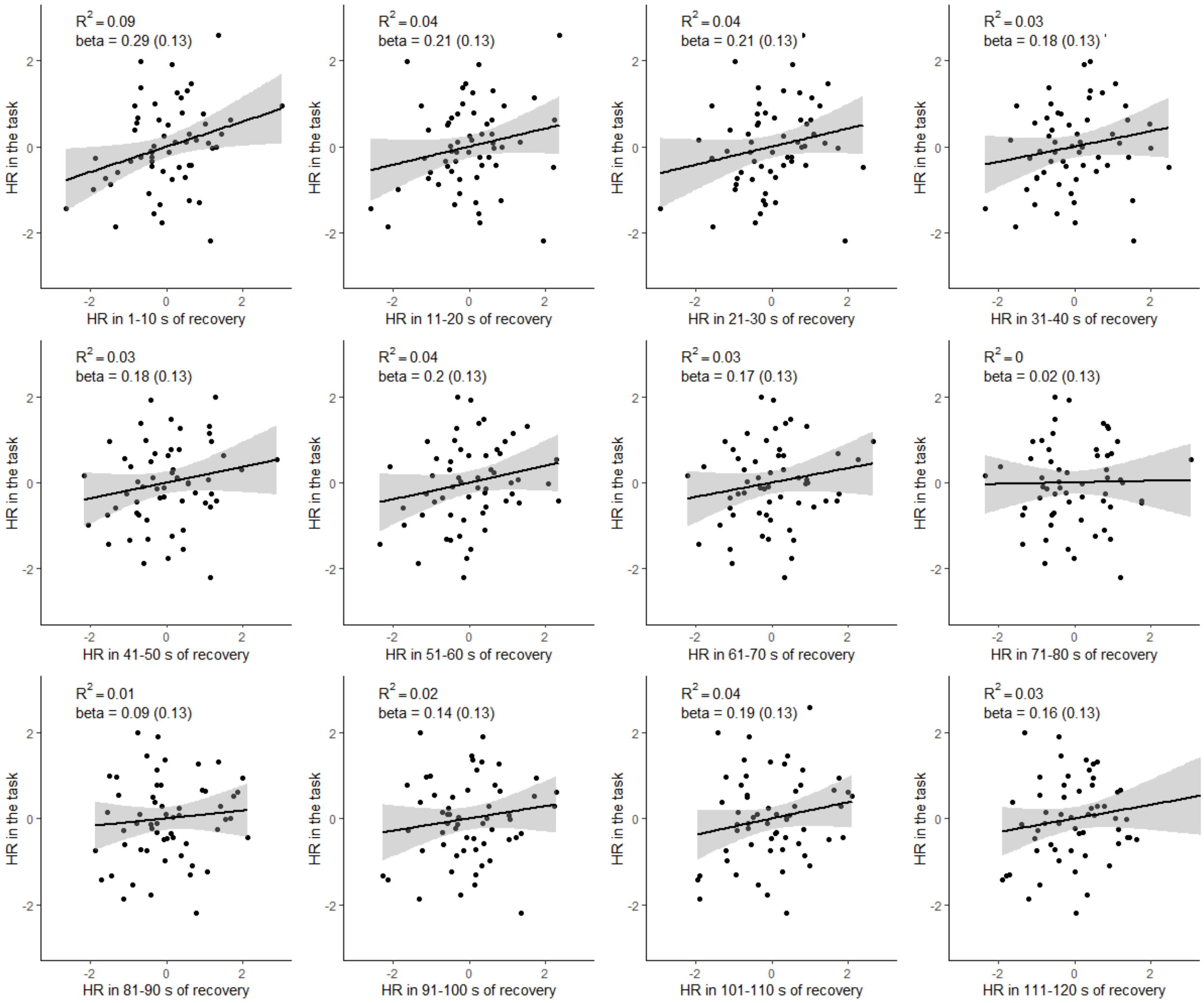
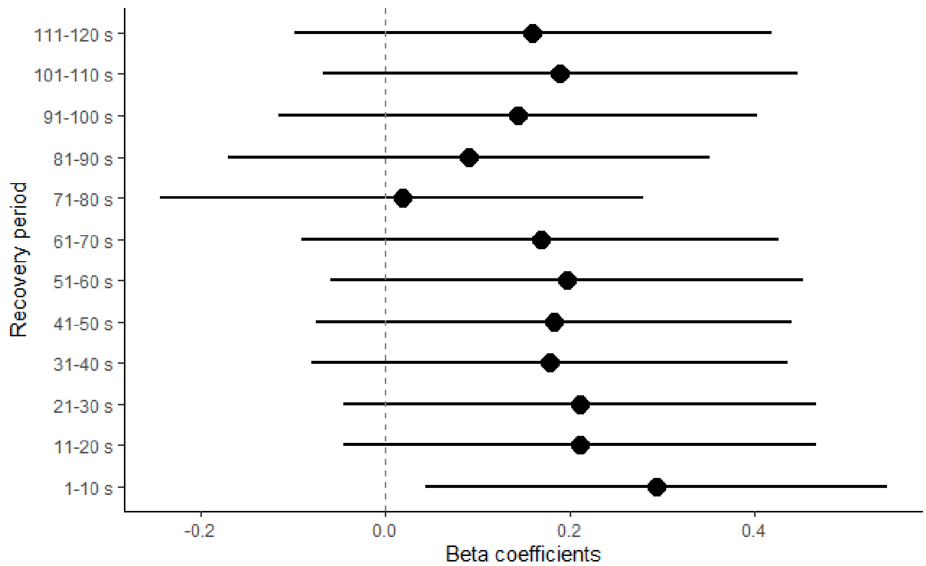


Figure S7. The relationship between HR reactivity in a task and 10-second segments of a recovery period (Study 1). The values in parentheses represent standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.



-

Figure S8. The beta coeffients from the regression analysis for HR (Study 1). The error bars represent 95% confidence intervals.

Predicting task assignment for HR

Table S10a

Summary of the logistic regression models predicting task condition using HR recovery scores from 10-second segments in Study 1

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	1.15	0.40	0.733	1.04	0.35	0.913	1.14	0.38	0.723	1.10	0.40	0.821	0.97	0.39	0.935	0.67	0.45	0.372
HR 10-sec recovery	0.98	0.05	0.651	0.99	0.04	0.868	0.98	0.04	0.624	0.99	0.04	0.766	1.00	0.04	0.913	1.05	0.05	0.268
Observations	58			58			58			58			58			58		
R^2 Tjur	.004			.000			.004			.002			.000			.021		

Table S10b

Summary of the logistic regression models predicting task condition using HR recovery scores from 10-second segments in Study 1 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	OR	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*	*OR*	*SE*	*p*
Intercept	0.72	0.42	.435	0.61	0.51	.334	0.84	0.52	.737	1.26	0.50	.648	0.86	0.47	.743	0.78	0.53	.645
HR 10-sec recovery	1.04	0.04	.317	1.06	0.05	.257	1.02	0.05	.698	0.98	0.04	.591	1.02	0.04	.693	1.02	0.04	.596
Observations	58			58			58			58			58			58		
R^2 Tjur	.017			.023			.003			.005			.003			.005		

Note. We did not provide adjusted p-values they all were insignificant even before the corrections.

Patterns of recovery for HR

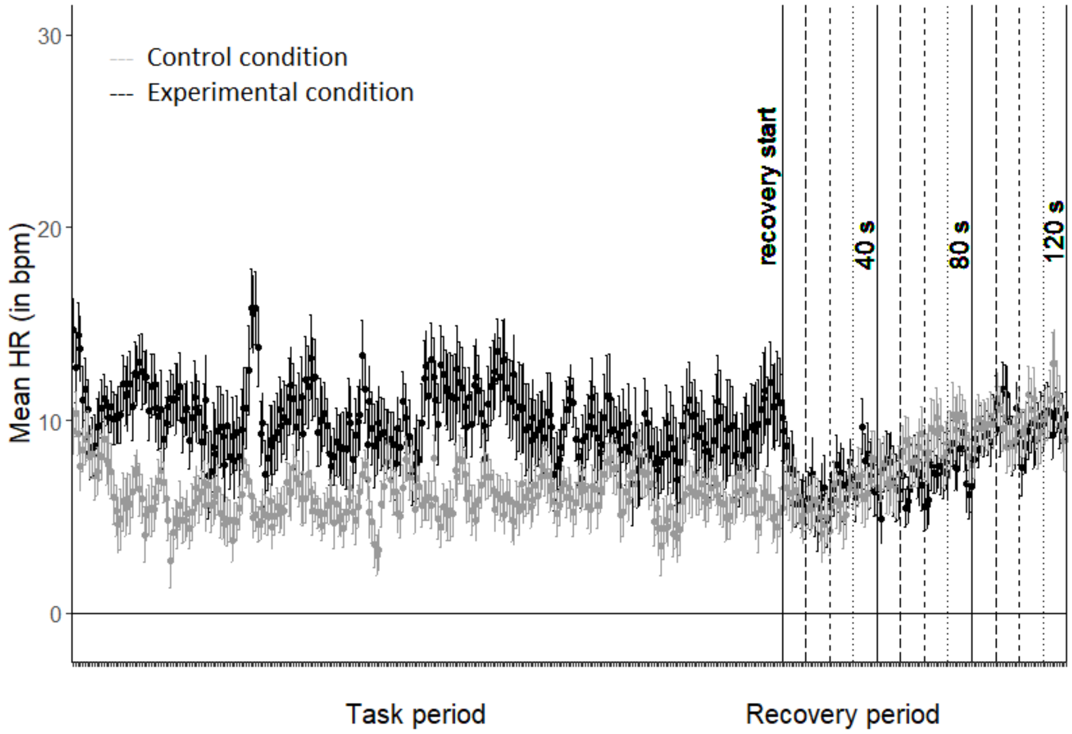


Figure S9. Average change scores of HR in the control and experimental conditions across task and recovery periods (Study 1). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.

Study 2

Table S11
Descriptive statistics and ICC for all the physiological measures in Study 1

	PEP			RB			RZ			HI	
Period	*M*	*SD*	*ICC*	*M*	*SD*	*ICC*	*M*	*SD*	*ICC*	*M*	*SI*
Baseline	122.91	13.99	.87	8.02	5.06	.83	148.89	19.03	.84	74.63	11.
Task	117.05	15.03	.64	72.30	7.86	.70	126.65	2.33	.57	85.13	14.
Recovery	119.3	12.06	.74	78.58	5.69	.70	143.60	18.88	.70	85.79	13.

Note. PEP, RB, and RZ are in ms, HR is in bmp.

Correlation between task and recovery scores: summary of the linear regression models

PEP

Table S12a
Summary of regression models of PEP task scores being predicted from 10-second segments of recovery in Study 2

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.09	.974	0.00	0.09	0.963	0.00	0.09	0.963	0.00	0.08	0.956	0.00	0.09	0.968	0.00	0.09	0.959
PEP 10-sec recovery	0.58	0.09	**<.001**	0.56	0.09	**<.001**	0.52	0.09	**<.001**	0.62	0.08	**<.001**	0.44	0.09	**<.001**	0.57	0.09	**<.001**
Adjusted p			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**			**<.001**
Observations	87			90			94			91			95			94		
R^2 / R^2 adjusted	.345 / .338			.313 / .305			.276 / .268			.388 / .381			.195 / .186			.321 / .314		

Table S12b
Summary of regression models of PEP task scores being predicted from 10-second segments of recovery in Study 2 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.08	0.958	0.00	0.08	0.983	0.00	0.08	0.983	0.00	0.08	0.963	0.00	0.08	0.974	0.00	0.08	0.963
PEP 10-sec	0.64	0.08	**<.001**	0.60	0.08	**<.001**	0.62	0.08	**<.001**	0.61	0.08	**<.001**	0.61	0.08	**<.001**	0.62	0.08	**<.001**

recovery						
Adjusted p	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Observations	96	90	91	92	93	95
R^2 / R^2 adjusted	.414 / .408	.359 / .352	.393 / .386	.378 / .371	.380 / .373	.392 / .385

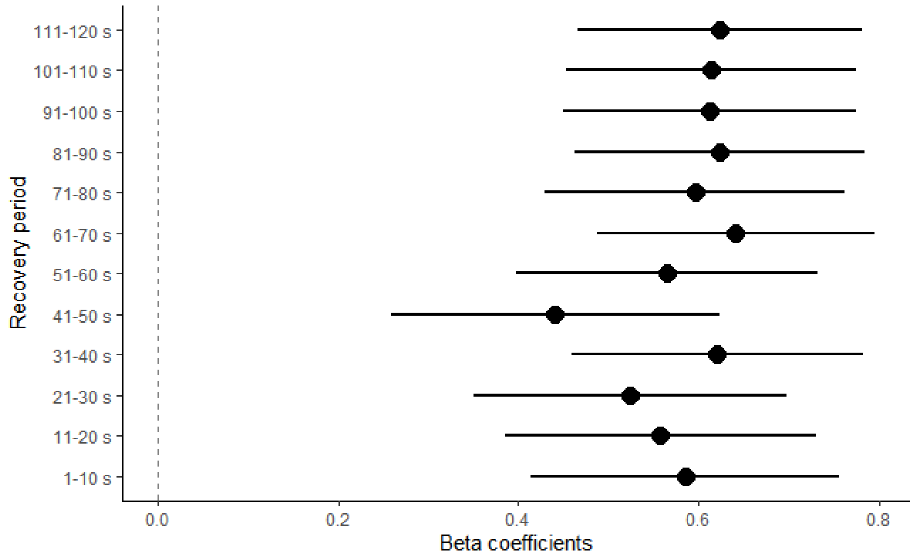


Figure S10. The beta coefficients from the regression analysis for PEP (Study 2). The error bars represent 95% confidence intervals.

RB

Table S13a

Summary of regression models of RB interval task scores being predicted from 10-second segments of recovery in Study 2

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.11	.995	0.00	0.10	.985	0.00	0.10	.994	0.00	0.10	.998	-0.00	0.10	.989	0.00	0.10	.996
RB 10-sec recovery	0.16	0.11	.155	0.20	0.10	.052	0.05	0.10	.610	0.04	0.10	.673	-0.09	0.10	.354	0.05	0.10	.602
Observations	83			95			102			101			103			104		
R^2 / R^2 adjusted	.025 / .013			.040 / .030			.003 / -.007			.002 / -.008			.009 / -.001			.003 / -.007		

Table S13b

Summary of regression models of RB interval task scores being predicted from 10-second segments of recovery in Study 2 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	-0.00	0.10	.995	-0.00	0.10	.999	-0.00	0.10	1.000	-0.00	0.10	.999	-0.00	0.10	.996	-0.00	0.10	.982
RB 10-sec recovery	-0.06	0.10	.550	-0.09	0.10	.385	-0.06	0.10	.549	-0.04	0.10	.684	-0.09	0.10	.383	-0.15	0.10	.127
Observations	107			102			103			104			104			104		
R^2 / R^2 adjusted	.003 / -.006			.008 / -.002			.004 / -.006			.002 / -.008			.007 / -.002			.023 / .013		

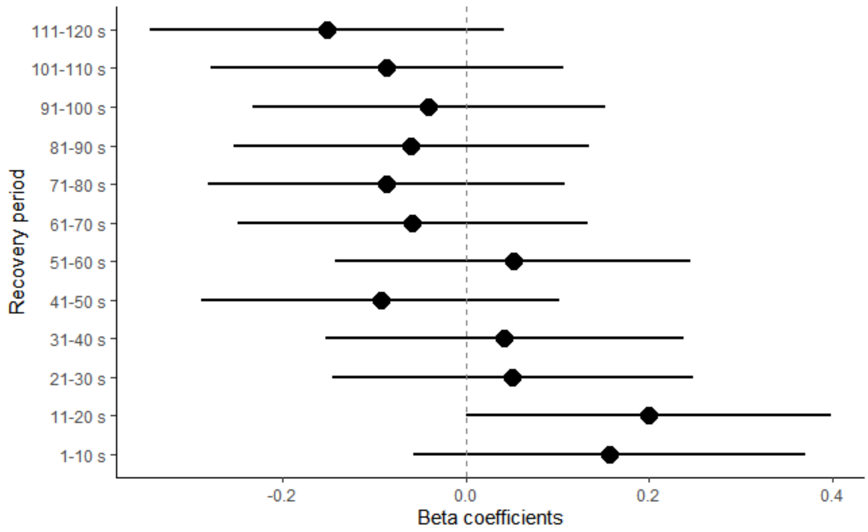


Figure S11. The beta coefficients from the regression analysis for RB interval (Study 2). The error bars represent 95% confidence intervals.

Summary of the repeated-measures models

Table S14

Summary of the repeated-measures models (Study 2)

	PEP			RB			RZ			HR		
Predictors	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*
(Intercept)	-8.10	1.67	**<.001**	-7.29	0.54	**<.001**	-21.43	1.63	**<.001**	11.17	1.23	**<.001**
Condition [Toy]	0.59	2.36	.802	0.73	0.73	.317	0.66	2.24	.768	0.90	1.70	.595
Condition [Bystanders]	2.60	2.39	.276	1.77	0.74	**.016**	6.74	2.23	**.003**	2.55	1.70	.134
Condition [Dog]	-0.59	2.32	.800	0.17	0.73	.819	-0.45	2.22	.838	-0.01	1.69	.997
Time	0.77	0.08	**<.001**	0.77	0.04	**<.001**	2.27	0.12	**<.001**	0.04	0.07	.562
Condition [Toy] * Time	-0.20	0.11	.064	-0.04	0.06	.514	-0.13	0.16	.435	-0.26	0.10	**.010**
Condition [Bystanders] * Time	-0.29	0.11	**.008**	-0.06	0.06	.278	-0.35	0.16	**.033**	-0.28	0.10	**.007**
Condition [Dog] * Time	-0.10	0.10	.330	0.00	0.06	.965	0.15	0.16	.367	-0.18	0.10	.076
Random Effects												
σ^2	20.24			6.58			52.84			23.03		
τ_{00}	66.15 $_{id}$			5.29 $_{id}$			53.83 $_{id}$			34.47 $_{id}$		
ICC	.77			.45			.50			.60		
N	105 $_{id}$			116 $_{id}$			118 $_{id}$			118 $_{id}$		
Observations	1130			1234			1300			1416		
Marginal R^2 / Conditional R^2	.064 / .781			.388 / .661			.384 / .695			.017 / .606		

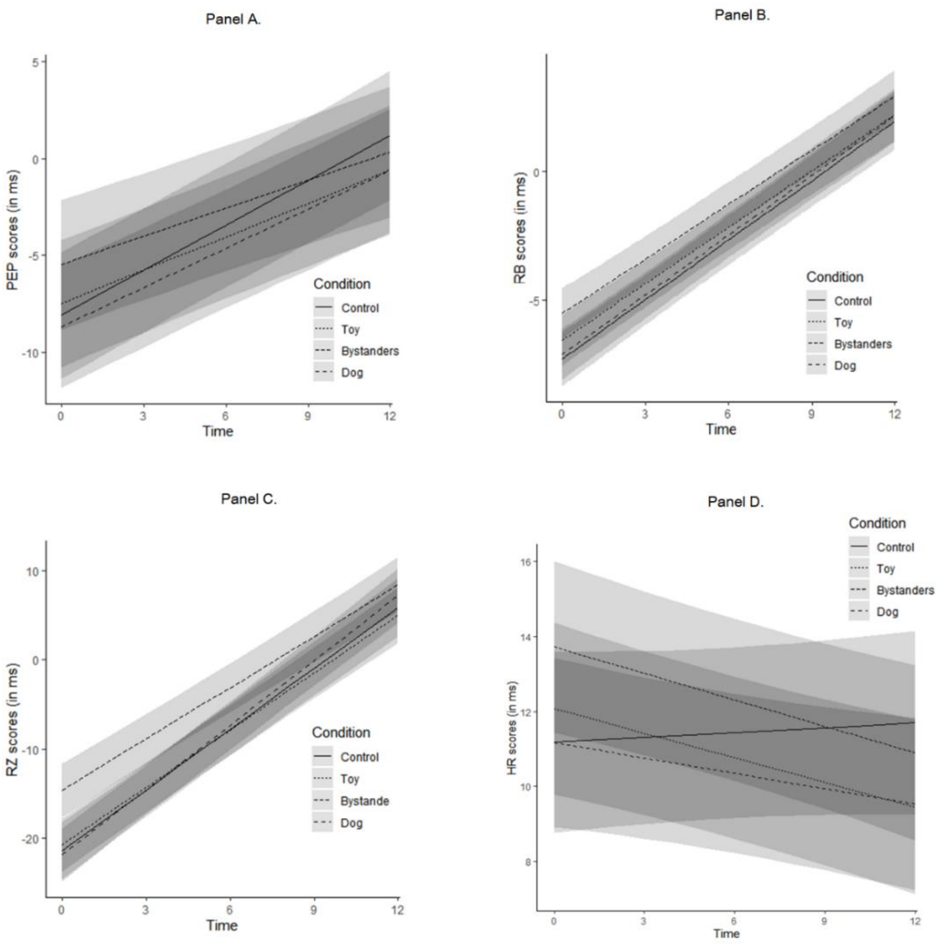


Figure S12. Predicted scores for the repeated measures analysis for PEP (Panel A), RB (Panel B), RZ (Panel C), and HR (Panel D) in Study 2. Grey shaded areas represent 95% confidence intervals.

Predicting condition assignment using recovery data: summary of the logistic regression models

Table S15a
Summary of the logistic regression models predicting task condition using RB interval recovery scores from 10-second segments in Study 2

	1-10 s			11-20 s			21-30 s			31-40 s			41-50 s			51-60 s		
	Odds Ratios	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*
(Intercept)	1.29	0.45	.573	1.81	0.43	.173	1.17	0.39	.690	1.29	0.42	.542	1.12	0.34	.737	1.69	0.32	.104
RB 10-sec recovery	1.01	0.06	.847	1.10	0.06	.113	1.02	0.07	.778	1.05	0.11	.670	1.04	0.10	.670	1.22	0.12	.113
Observa	42			46			50			47			47			49		

tions																		
R^2 Tjur	.001			0.059			.002			.004			.004			.056		

Table S15b
Summary of the logistic regression models predicting task condition using RB interval recovery scores from 10-second segments in Study 2 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	Odds Ratios	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*
Intercept	1.37	0.29	.280	1.38	0.30	.278	1.32	0.29	.335	1.18	0.30	.572	1.14	0.30	.662	1.10	0.29	.746
RB 10-sec recovery	1.21	0.11	.084	1.17	0.12	.197	1.04	0.09	.643	1.13	0.11	.251	1.18	0.13	.208	1.16	0.15	.312
Observations	51			49			49			51			50			50		
R^2 Tjur	.061			.034			.004			.025			.032			.020		

Analysis for RZ interval

We manually removed 10%, 27%, and 11% of the data in the baseline, task, and the recovery period, respectively for RZ interval in Study 2.

Relationship between task and recovery scores for RZ interval

Table S16a

Summary of regression models of RZ interval task scores being predicted from 10-second segments of recovery in Study 2

	1-10 s			11-20 s			21-30 s			31-40 s			41-50 s			51-60 s		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.10	.989	0.00	0.09	.975	0.00	0.09	.967	0.00	0.09	.990	0.00	0.09	.992	0.00	0.09	.983
RZ 10-sec recovery	0.25	0.10	**.015**	0.31	0.09	**.001**	0.29	0.09	**.003**	0.20	0.09	**.041**	0.20	0.09	**.042**	0.29	0.09	**.002**
Adjusted p			.025			.009			.009			.046			.046			.009
Observations	92			105			107			108			108			109		
R^2 / R^2 adjusted	.064 / .053			.096 / .087			.083 / .075			.039 / .030			.038 / .029			.086 / .078		

Table S16b

Summary of regression models of RZ interval task scores being predicted from 10-second segments of recovery in Study 2 (continuation)

	61-70 s			71-80 s			81-90 s			91-100 s			101-110 s			111-120 s		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.09	.986	-0.00	0.10	.999	-0.00	0.09	.997	0.00	0.09	.999	0.00	0.09	.995	0.00	0.10	.983
RZ 10-sec recovery	0.25	0.09	**.007**	0.15	0.10	.122	0.27	0.09	**.004**	0.23	0.09	**.017**	0.28	0.09	**.003**	0.22	0.10	**.022**
Adjusted p			.015			.122			.009			.025			.009			.029
Observations	111			109			109			108			107			106		
R^2 / R^2 adjus	.064 / .055			.022 / .013			.076 / .067			.053 / .044			.082 / .073			.049 / .040		

ted

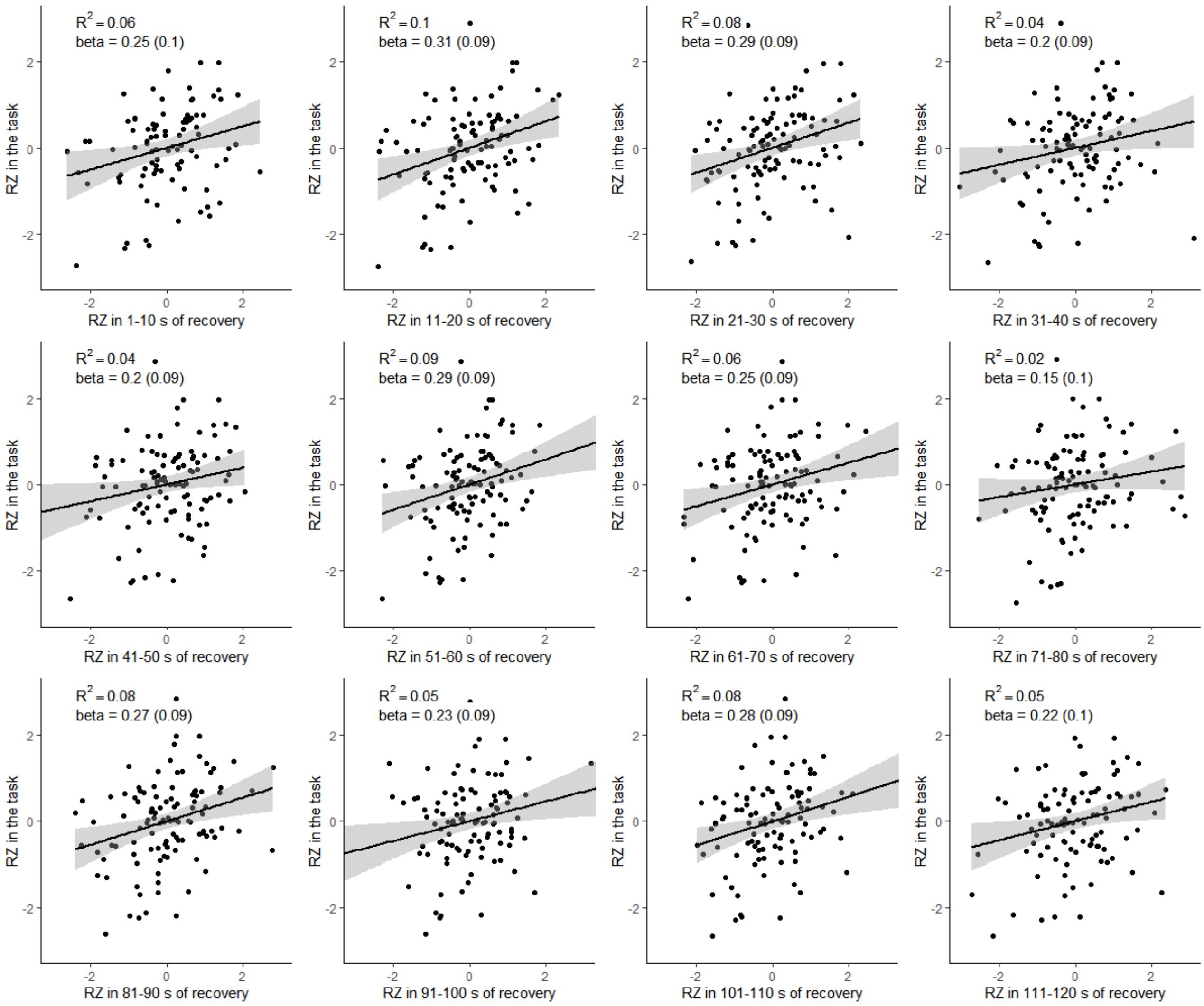


Figure S13. The relationship between RZ interval reactivity in a task and 10-second segments of a recovery period (Study 2). The values in parentheses represent standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

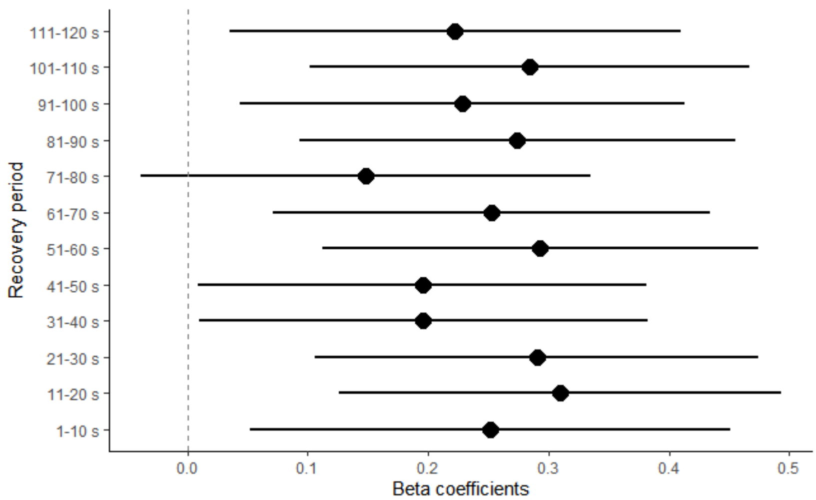


Figure S14. The beta coeffients from the regression analysis for RZ interval (Study 2). The error bars represent 95% confidence intervals.

Predicting condition assignment for RZ interval

Table S17a
Summary of the logistic regression models predicting task condition using RZ interval recovery scores from 10-second segments in Study 2

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	Odds Ratios	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*
Intercept	2.09	0.53	.167	2.19	0.49	.112	1.54	0.43	.315	1.58	0.37	.223	1.40	0.34	.317	1.72	0.33	.105
RZ 10-sec recovery	1.03	0.03	.231	1.04	0.03	.091	1.02	0.03	.387	1.04	0.03	.160	1.04	0.03	.213	1.08	0.04	**.044**
Adjusted p			.308			.258			.465			.274			.308			.258
Observations	45			51			52			53			51			53		
R^2 Tjur	.033			.059			.015			.041			.031			.092		

Table S17b
Summary of the logistic regression models predicting task condition using RZ interval recovery scores from 10-second segments in Study 2 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	Odds Ratios	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*	*Odds Ratios*	*std. Error*	*p*
Intercept	1.29	0.29	.382	1.21	0.28	.500	1.07	0.28	.813	1.15	0.28	.621	1.08	0.30	.792	1.10	0.29	0.745
RZ 10-sec recovery	1.07	0.03	**.033**	1.02	0.03	.459	1.02	0.03	.546	1.05	0.03	.107	1.07	0.04	.079	1.06	0.04	0.155
Adjusted p			.258			.501			.546			.258			.258			0.274
Observations	53			53			52			54			51			52		
R^2 Tjur	.095			.010			.007			.051			.066			.040		

Patterns of recovery for RZ interval

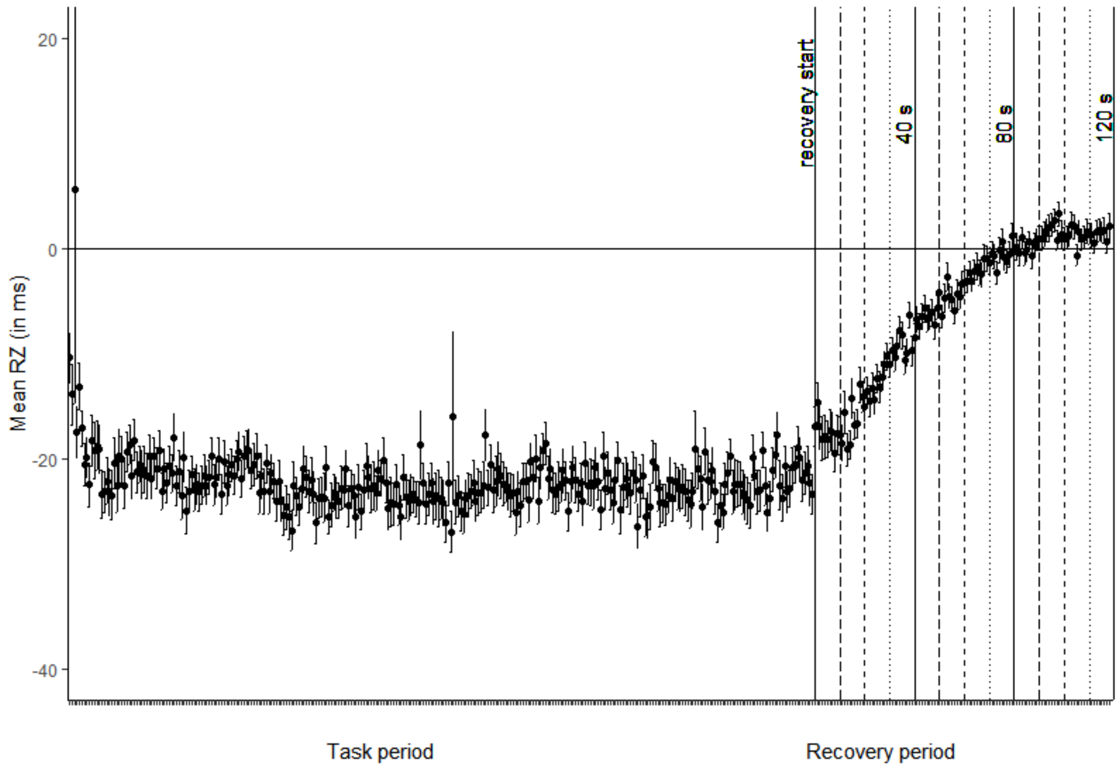


Figure S15. Average change scores of RZ interval in the control and experimental conditions across task and recovery periods (Study 2). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.

Analysis for HR interval

Relationship between task and recovery scores for HR

Table S18a

Summary of regression models of HR task scores being predicted from 10-second segments of recovery in Study 2

	1-10 s			**11-20 s**			**21-30 s**			**31-40 s**			**41-50 s**			**51-60 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000
HR 10-sec recovery	0.20	0.09	**.027**	0.18	0.09	.055	0.04	0.09	.662	-0.12	0.09	.205	-0.13	0.09	.152	-0.07	0.09	.457
Adjusted p			.164			.219			.722			.351			.351			.609
Observations	118			118			118			118			118			118		
R^2 / R^2 adjusted	.041 / .033			.031 / .023			.002 / .007			.014 / .005			.018 / .009			.005 / <.001		

Table S18b

Summary of regression models of HR task scores being predicted from 10-second segments of recovery in Study 2 (continuation)

	61-70 s			**71-80 s**			**81-90 s**			**91-100 s**			**101-110 s**			**111-120 s**		
	beta	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*	*beta*	*SE*	*p*
Intercept	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000	0.00	0.09	1.000
HR 10-sec recovery	-0.02	0.09	.801	-0.12	0.09	.184	-0.10	0.09	.290	-0.13	0.09	.164	-0.21	0.09	**.025**	-0.05	0.09	.624
Adjusted p			.801			.351			.434			.351			.164			.722
Observations	118			118			118			118			118			118		
R^2 / R^2 adjusted	.001 / <.001			.015 / .007			.010 / .001			.017 / .008			.042 / .034			.002 / <.001		

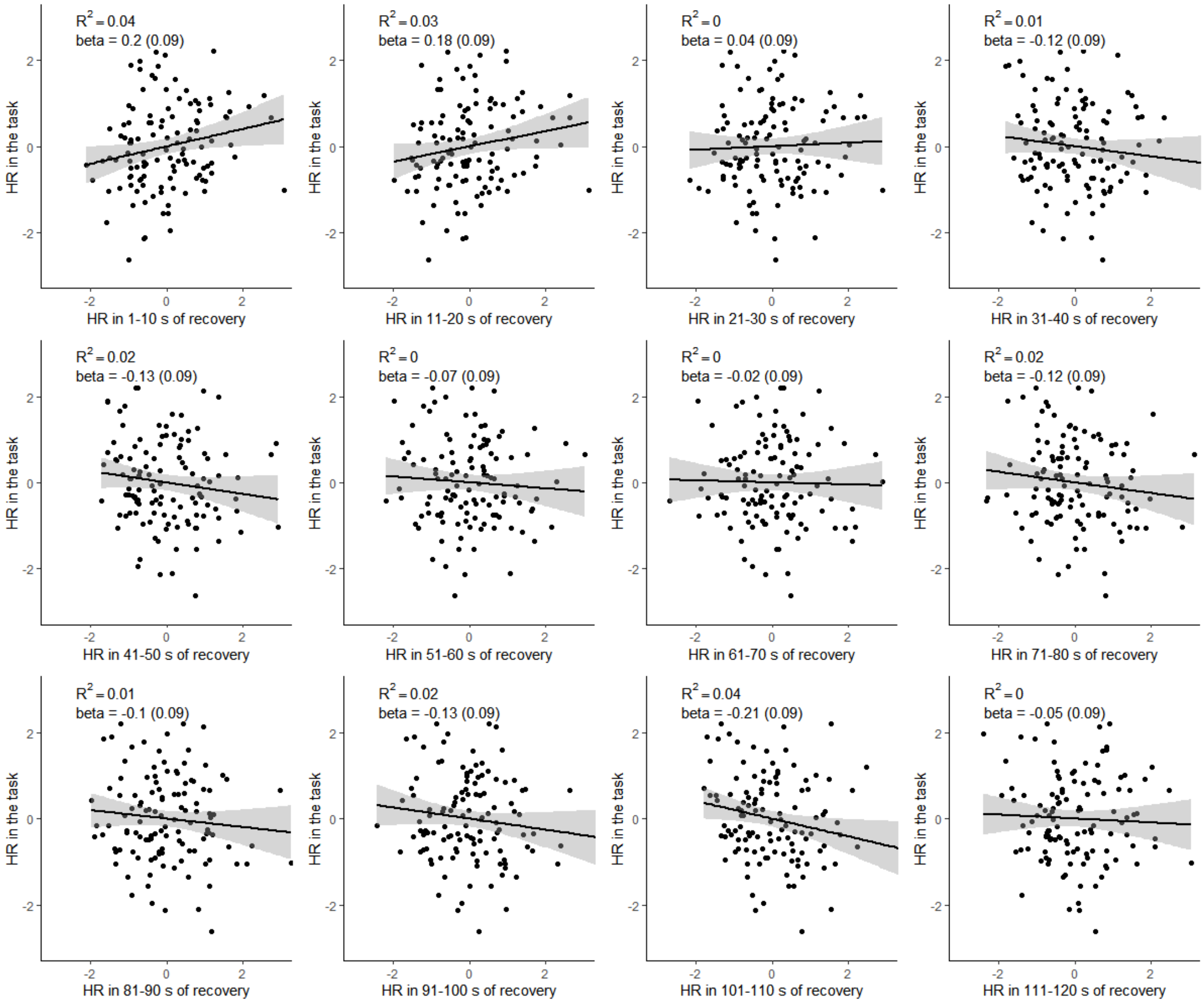


Figure S16. The relationship between HR reactivity in a task and 10-second segments of a recovery period (Study 2). The values in parentheses represent standard error of the beta coefficients. Grey shaded areas represent 95% confidence intervals.

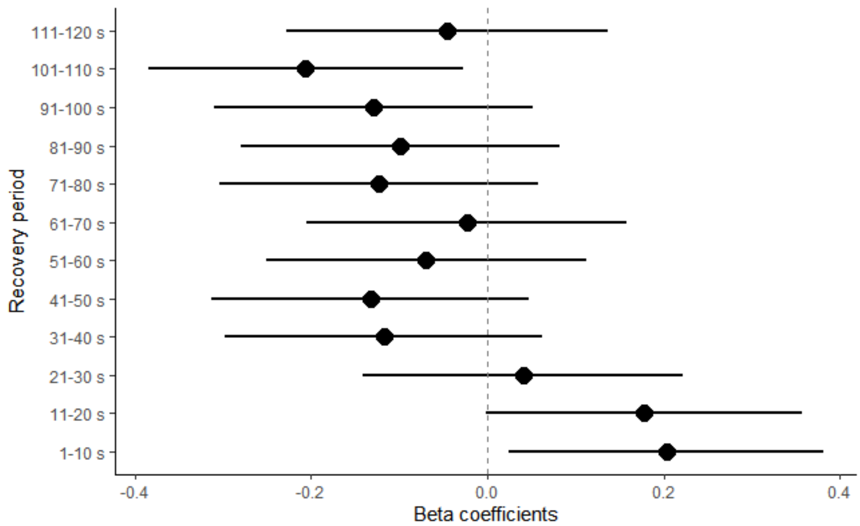


Figure S17 . The beta coeffients from the regression analysis for HR (Study 2). The error bars represent 95% confidence intervals.

Patterns of recovery for HR

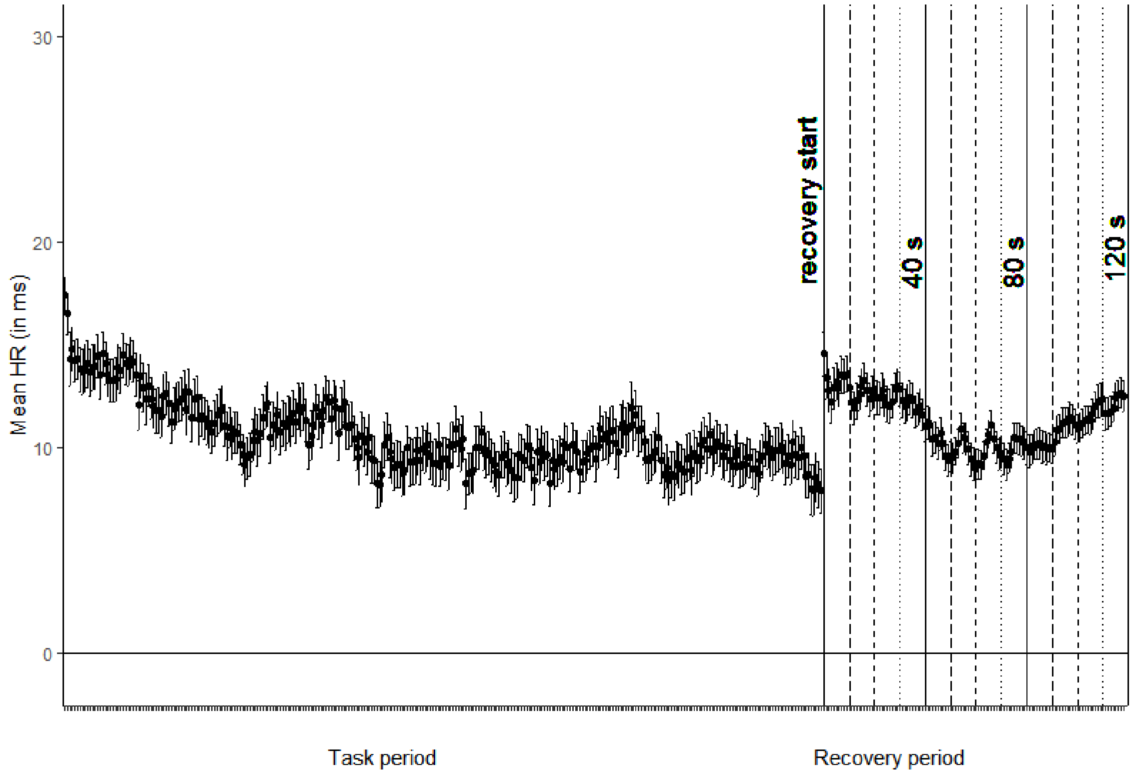


Figure S18. Average change scores of HR in the control and experimental conditions across task and recovery periods (Study 2). The error bars represent +/- 1 SE. The vertical lines mark every 10-second segment in the recovery.