Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Peer-Led Examination Simulation Reshapes Psychophysiological and Emotional State Profiles During Problem-Based Medical Learning

Morris Gellisch

morris.gellisch@ruhr-uni-bochum.de

Ruhr University Bochum

Thorsten Schäfer

Ruhr University Bochum

Article

Keywords:

Posted Date: July 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9931568/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at npj Science of Learning on October 24th, 2026. See the published version at https://doi.org/10.1038/s41539-026-00459-x.

Peer-Led Examination Simulation Reshapes Psychophysiological and Emotional State Profiles During Problem-Based Medical Learning

Morris Gellisch[1], Thorsten Schäfer[1]

[1] Center for Medical Education, Ruhr-University Bochum, 44801 Bochum, Germany

Correspondence to: morris.gellisch@ruhr-uni-bochum.de

Abstract

Problem-based learning is widely assumed to activate students through self-directed inquiry, collaborative reasoning, and contextualized problem solving, yet the psychophysiological and achievement-emotional state dynamics generated by regular PBL sessions remain poorly characterized. In particular, familiar PBL routines may not always provide sufficient salience, accountability, or retrieval-related activation to fully engage the learner states they are intended to promote. This repeated-measures study examined whether embedding a peer-led examination simulation into regular PBL reshapes students' psychophysiological and achievement-emotional state profiles during medical learning. Forty-two medical students were assessed across resting baseline, regular PBL, and PBL with peer-led examination simulation. Heart rate variability was recorded during two 5-minute performance intervals per learning condition and analyzed using RMSSD, SDNN, pNN50, and LF/HF ratio. Psychological measures captured social interaction anxiety, perceived stress, state anxiety, achievement emotions, self-rated performance, and post-session appraisal.

Both PBL formats reduced heart rate variability relative to baseline, indicating that regular PBL itself constituted an autonomically active learning state. Compared with regular PBL, peer-led examination simulation induced additional HRV withdrawal, reflected by lower RMSSD,

SDNN, and pNN50, whereas LF/HF did not show a robust condition effect. Baseline-adjusted interval-level mixed models replicated the examination-simulation effect for RMSSD, SDNN, and pNN50. At the achievement-emotional level, the simulation increased anxiety and perceived stress while reducing boredom. Enjoyment, motivation, and self-rated performance remained stable. Students also reported greater perceived benefit from, and stronger preference for, the examination-simulation format. Exploratory analyses further indicated that stronger increases in anxiety were associated with stronger additional RMSSD withdrawal, suggesting convergence between achievement-emotional activation and autonomic regulation.

These findings show that peer-led examination simulation does not merely add stress to PBL, but shifts the learning episode toward a more salient, assessment-like, and educationally valued psychophysiological state without compromising students' motivation. More broadly, the study positions psychophysiological measurement as a tool for examining how instructional design modulates achievement-emotional dynamics, attentional engagement, and autonomic regulation during authentic medical learning.

Introduction

Problem-based learning (PBL) is an established instructional approach in medical education that organizes learning around authentic, complex problems rather than around the passive reception of discipline-based content[1,2]. In PBL, students typically work in small groups to activate prior knowledge, identify knowledge gaps, formulate learning objectives, engage in self-directed inquiry, and collaboratively integrate new knowledge into a shared understanding of the problem[3]. Originating from curriculum reform in medical education, most prominently at McMaster University, PBL was developed to bring learning closer to the intellectual demands of clinical reasoning and professional practice[4,5]. Its enduring appeal lies in a simple but powerful premise: medical knowledge is learned most meaningfully when it is actively

constructed, negotiated, and applied in context. Conceptually, PBL builds on constructive, self-directed, collaborative, and contextual learning principles and is therefore considered particularly suited to strengthening clinical reasoning, problem-solving, and professional competencies[6,7]. In many medical curricula, however, PBL is not necessarily implemented as the sole organizing principle of the entire programme, but rather as a deliberately embedded small-group format within broader undergraduate or preclinical teaching structures. This makes individual PBL sessions important curricular spaces in which selected biomedical or clinically oriented content can be transformed into problem-oriented, student-centred learning.

Yet the promise of PBL is not automatically realized once students are placed around a problem. Its effectiveness depends on whether the learning environment generates sufficient cognitive, emotional, and social activation to sustain the very processes PBL is designed to promote: elaboration, motivation, collaborative reasoning, and self-directed inquiry. When such activation remains low, PBL may remain structurally present but pedagogically underpowered, limiting the extent to which its intended learning processes are expressed across groups, sessions, and individual learners[8]. This raises an important question for learning research: what kinds of learner states are actually generated within PBL environments, and how do these states relate to engagement, attention, and learning-related behavior?

Learning does not occur in a physiologically neutral state. Educational situations are accompanied by emotional and autonomic dynamics that shape attention, engagement, knowledge retrieval, and behavioral regulation[9,10]. Achievement emotions such as enjoyment, anxiety, and boredom are closely linked to motivation, cognitive resources, self-regulated learning, and academic performance, indicating that the emotional tone of a learning environment is functionally relevant for learning[11,12]. At the neurobiological level, arousal-related systems provide a mechanistic basis for this relationship: sympathetic-adrenomedullary and hypothalamic-pituitary-adrenal activation modulate catecholaminergic and glucocorticoid

signaling, thereby influencing amygdala, hippocampal, prefrontal, and striatal networks involved in attention, memory, and cognitive control[13–15]. From this perspective, autonomic regulation provides a peripheral window into how learners adapt to the demands of an educational situation[16]. Sympathetic activation and parasympathetic withdrawal reflect the mobilization of bodily resources, while vagally mediated heart rate variability is closely linked to top-down regulatory capacity, cognitive control, and flexible adaptation to changing task demands[17,18]. Importantly, however, the effects of stress and arousal are not linear. Moderate, task-relevant, and temporally aligned arousal may support attentional mobilization and memory formation, whereas excessive or prolonged stress can impair retrieval, cognitive control, and performance[19–21]. Physiological arousal in learning environments should therefore not be interpreted as inherently beneficial or harmful, but as a context-dependent marker of engagement whose educational meaning depends on intensity, timing, and subjective appraisal. If arousal is context-dependent, it can also be pedagogically designed. In protected learning environments, moderate assessment-like activation may be used strategically to increase attention, accountability, and emotional involvement without converting the situation into a high-stakes threat. Examination simulation offers a concrete mechanism for this purpose. Previous psychophysiological work has shown that simulated oral examination formats, both lecturer-led and peer-led, can evoke measurable physiological arousal in educational settings[22]. Applied to PBL, such simulation may act as a controlled perturbation of a familiar learning routine: it preserves the collaborative, student-centred structure of PBL while adding assessment-like salience that may counteract habituation, underarousal, and reduced engagement.

Against this background, the present study investigated whether implementing a peer-led examination simulation into a regular PBL session changes the emotional and autonomic state architecture of medical students. Rather than aiming to quantify short-term knowledge gains, the study focused on the autonomic and emotional embedding of the learning environment

itself: that is, on how an assessment-like, socially embedded instructional episode modulates physiological regulation, achievement-related emotions, perceived stress, and motivational appraisal while learning unfolds. We therefore conceptualized peer-led examination simulation not simply as an assessment rehearsal, but as a controlled didactic perturbation of PBL designed to increase assessment-like salience while preserving the collaborative and student-led character of the learning environment.

To capture this learning-related state profile, we combined heart rate variability as a marker of autonomic regulation with psychological measures of social interaction anxiety, perceived stress, anxiety, boredom, enjoyment, motivation, self-rated performance, and post-session appraisal. This multimodal approach allowed us to examine whether peer-led examination simulation elicited HRV-based evidence of physiological arousal, whether this arousal co-occurred with systematic changes in achievement-related emotional and motivational states, and whether individual differences in social-evaluative sensitivity modulated students' affective and autonomic responses. Finally, we explored psychophysiological coupling between emotional activation and vagally mediated HRV withdrawal to test whether subjective anxiety and autonomic regulation converged within the same instructional episode.

Materials and Methods

Study design and setting

This study used a repeated-measures psychophysiological design embedded in a regular problem-based learning course within the preclinical medical curriculum at Ruhr University Bochum. The study compared students' autonomic and psychological responses across three within-person states: a resting baseline, a regular problem-based learning condition, and an extended problem-based learning condition incorporating a peer-led examination simulation.

The regular PBL condition represented the established course format. Physiological measurements were obtained during step 7 of the PBL cycle, in which students presented, discussed, and integrated the results of their self-directed learning phase within the group. The examination-simulation condition was implemented as an extension of the same curricular PBL context. In this condition, the regular presentation and discussion phase was replaced by a peer-led oral examination simulation, in which students were questioned by a student-led examination committee on the learning objectives and content of the PBL case.

Heart rate variability was recorded during the most performance-relevant phase of each learning condition. For each participant, two predefined 5-minute intervals were extracted during regular PBL and two corresponding 5-minute intervals during the peer-led examination simulation. A resting baseline measurement was included to characterize individual autonomic regulation outside the active learning conditions. Psychological measures were collected to assess social interaction anxiety, perceived stress, state anxiety, achievement emotions, self-rated performance, and post-session appraisal of the learning formats.

Participants

Forty-two third-semester medical students participated in the study. All participants were enrolled in the preclinical medical curriculum at Ruhr University Bochum and attended the PBL course in which the study was embedded. Participation was voluntary, and all participants provided written informed consent prior to data collection. No participants were excluded from the analyses, and complete physiological and psychological datasets were available for all 42 participants: 23 female students (54.76%) and 19 male students (45.24%). On average, the students in the sample cohort were 20.98 years old (SD = 2.98). The mean age of the sample was 20.98 years (SD = 2.98). Male students had a mean age of 21.47 years (SD = 4.09), whereas female students had a mean age of 20.57 years (SD = 1.53).

Inclusion criteria

Participants were recruited from the third preclinical semester of the medical curriculum at Ruhr University Bochum. Eligible participants were required to be formally enrolled as medical students and to attend the respective PBL course in which the study was embedded. During recruitment, we aimed to obtain a balanced gender distribution and to include students irrespective of gender identity, religious affiliation, or ethnic background. This inclusive recruitment strategy was intended to reflect the diversity of the medical student cohort and to support the applicability of the findings to comparable undergraduate medical education settings.

Heart Rate Variability measurements

Heart rate variability was recorded using the Polar Vantage V2 together with the Polar H10 chest strap sensor (Polar Electro Oy, Kempele, Finland). The Polar H10 was selected because previous validation work has shown high agreement with electrocardiography-derived RR intervals and linear heart rate parameters, supporting its use for HRV assessment in applied research settings[23]. HRV recording was embedded into both the regular PBL session and the peer-led examination simulation using a standardized measurement protocol. In the regular PBL condition, HRV was extracted individually during step 7 of the PBL cycle, when students presented and discussed the results of their self-directed learning phase within the group. For each participant, two predefined 5-minute intervals were selected from this presentation phase to obtain short-term HRV segments suitable for time-domain and frequency-domain analysis. In the PBL + examination simulation condition, HRV was likewise extracted from two predefined 5-minute intervals during the period in which the respective participant was examined by the peer-led examination committee. Thus, HRV was assessed during the most performance-relevant phase of each learning format: the presentation and discussion phase in

regular PBL and the individual oral examination phase in the simulation-enhanced PBL condition. In accordance with the standards proposed by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology[24], HRV analysis included both time-domain and frequency-domain parameters. Time-domain indices comprised RMSSD, SDNN, and pNN50, while frequency-domain analysis included low-frequency power, high-frequency power, and the LF/HF ratio. Spectral components were derived using a fast Fourier transform algorithm. RMSSD and pNN50 were interpreted primarily as indices of vagally mediated HRV, whereas SDNN was used as a broader marker of overall heart rate variability. The LF/HF ratio was included as an exploratory frequency-domain parameter and interpreted cautiously, given ongoing debate regarding its physiological specificity.

Psychological measures

Social interaction anxiety was assessed using the Social Interaction Anxiety Scale (SIAS), a validated instrument designed to capture anxiety in social interaction situations[25]. The SIAS was included as a person-level measure of social-evaluative sensitivity that may shape students' affective and physiological responses during peer-led examination simulation. In the present sample, the SIAS showed high internal consistency (Cronbach's $\alpha = .885$).

Learning-related emotions were assessed using validated items derived from the achievement-emotions framework, focusing on enjoyment, anxiety, and boredom as central emotional states in academic learning and performance contexts[26]. These items were selected because achievement emotions are theoretically and empirically linked to motivational engagement, cognitive resource allocation, self-regulated learning, and performance-related appraisal. By including both activating and deactivating emotions, the questionnaire captured whether the peer-led examination simulation produced a differentiated emotional learning profile rather

than a nonspecific stress response alone. Internal consistency was good in both learning conditions for enjoyment (regular PBL: α = .840; examination simulation: α = .850), anxiety (regular PBL: α = .804; examination simulation: α = .849), and boredom (regular PBL: α = .853; examination simulation: α = .783). Because anxiety and boredom may fluctuate rapidly in response to situational demands, both emotions were additionally assessed as state-level experiences using visual analogue scales, allowing their immediate intensity to be captured in close temporal proximity to the respective learning condition.

In addition, visual analogue scales (VAS) were used to capture situation-specific psychological states with high temporal proximity to the learning events[27]. VAS instruments are well suited for time-sensitive educational and psychophysiological research because they allow rapid, low-burden assessment of subjective states that are closely tied to a specific instructional episode. In the present study, VAS ratings were used to assess state anxiety, perceived stress, motivation and self-rated performance[28]. Perceived stress was measured at three time points - before, during, and after the respective learning condition - to characterize the temporal stress profile of regular PBL and PBL with peer-led examination simulation.

Finally, post-session appraisal items were used to assess students' perceived educational benefit, format preference, and perceived adequacy of the examination simulation as an alternative or extension to the regular PBL format. Together, these measures enabled us to characterize not only whether the peer-led examination simulation elicited stress or anxiety, but whether it produced a broader learning-related emotional and evaluative profile.

Ethical aspects

This research was conducted in accordance with the principles outlined in the Declaration of Helsinki. Approval for the study was obtained from the *Ethics Committee of the Professional*

School of Education at Ruhr University Bochum (Reference No. EPSE-2022-004, dated 12.09.2022). The study adhered to all ethical guidelines to ensure the safety, well-being, and confidentiality of all participants.

Statistics

All analyses were based on the repeated-measures structure of the study, with each participant contributing observations from the regular PBL condition, the PBL + examination simulation condition, and the resting baseline where applicable. HRV data were organized at the participant-by-condition-by-interval level, whereas psychological outcomes were analyzed as within-person condition contrasts between regular PBL and PBL + examination simulation. Descriptive statistics are reported as means and standard deviations as well as medians, interquartile ranges, and observed ranges to characterize both central tendency and distributional variability.

For HRV analyses, short-term segments of 5 minutes were used in accordance with established HRV recommendations. Time-domain indices included RMSSD, SDNN, and pNN50; frequency-domain analysis included LF, HF, and the LF/HF ratio. RMSSD, SDNN, and LF/HF were analyzed on the logarithmic scale when required to reduce skewness and improve model assumptions, while descriptive values are reported on the original metric for interpretability. For each participant and condition, interval-level HRV values were retained for mixed-model analyses, and condition-level total values were computed by averaging the two 5-minute intervals. This allowed us to examine both phase-level differences and the robustness of condition effects across repeated physiological segments.

Primary within-person comparisons tested whether regular PBL differed from resting baseline and whether PBL + examination simulation differed from regular PBL. Paired-samples t-tests

were used for condition contrasts on the appropriate analysis scale. Effect sizes for paired comparisons are reported as Cohen's dz, together with mean differences and 95% confidence intervals. This analysis provided a direct estimate of the magnitude of autonomic and psychological change induced by the examination-simulation extension.

To account for the nested structure of the HRV data and to avoid reducing the physiological signal to a single aggregate per participant, we additionally fitted interval-level linear mixed-effects models. These models included participant-specific random intercepts and estimated the effect of examination simulation while adjusting for resting baseline HRV and measurement interval. Separate models were fitted for RMSSD, SDNN, pNN50, and LF/HF. Model predictors were standardized where appropriate, allowing fixed-effect estimates to be interpreted as standardized differences. This modelling strategy was used to test whether the examination-simulation effect remained robust after accounting for individual baseline autonomic regulation and repeated interval measurements.

Psychological outcomes were analyzed using paired within-person comparisons between regular PBL and PBL + examination simulation. For post-session appraisal, paired comparisons examined whether students reported greater perceived benefit from, and preference for, the examination format compared with the regular PBL format.

To examine whether individual differences in social-evaluative sensitivity shaped students' responses to the peer-led examination simulation, exploratory mixed models included Social Interaction Anxiety Scale scores as a standardized person-level predictor. These models estimated the main effect of condition, the main effect of SIAS, and the condition × SIAS interaction for selected affective, appraisal-related, and autonomic outcomes. This approach allowed us to distinguish between the general effect of the examination simulation and interindividual susceptibility to social-evaluative demands.

Finally, exploratory psychophysiological coupling analyses tested whether changes in subjective emotional activation were associated with changes in autonomic regulation. Specifically, condition-related changes in anxiety were related to additional RMSSD withdrawal from regular PBL to PBL + examination simulation. Complementary regression and mixed-model analyses were used to examine whether subjective anxiety and vagally mediated HRV converged as coordinated markers of the same assessment-like learning state.

For the temporal stress profile, perceived stress ratings obtained before, during, and after each learning condition were analyzed using categorical mixed-effects models with participant-specific random intercepts. Fixed effects included condition, time point, and their interaction, with SIAS included as an additional person-level predictor in exploratory moderation models. This analysis tested whether the examination simulation altered not only the level of perceived stress but also its temporal trajectory across the learning episode.

Statistical significance was evaluated using two-sided tests with an alpha level of .05. Emphasis was placed on effect sizes, confidence intervals, and convergence across paired comparisons, interval-level mixed models, and psychophysiological coupling analyses rather than on isolated p-values alone.

Sensitivity Analysis

A sensitivity analysis for the paired within-person contrasts indicated that the present sample size was well aligned with the magnitude of the observed primary effects. The central autonomic and psychological outcomes showed medium-sized within-person effects, including log-RMSSD, perceived stress, boredom, and anxiety, for which statistical power was high at $\alpha = .05$. This supports the interpretation that the study was sufficiently sensitive to detect the core psychophysiological activation profile induced by the peer-led examination simulation.

Results

Overview of the analytic structure

The analyses followed the repeated-measures structure of the study. Heart rate variability (HRV) outcomes were analyzed across resting baseline, regular problem-based learning (PBL), and PBL with peer-led examination simulation. Psychological outcomes were analyzed as within-person contrasts between regular PBL and PBL with examination simulation. For HRV, each participant contributed two 5-minute intervals per learning condition, allowing both condition-level paired comparisons and interval-level mixed-effects modelling. Descriptive statistics for HRV parameters are presented in Table 1; descriptive statistics for psychological measures and post-session appraisal are presented in Table 2.

Table 1. Descriptive statistics of heart rate variability parameters across baseline, regular PBL, and PBL with peer-led examination simulation

Marker	Phase	Interval	n	M (SD)	Mdn [IQR]	Range
RMSSD	Baseline	1	42	48.48 (25.83)	39.52 [28.89]	19.09-106.73
RMSSD	Baseline	2	42	44.01 (22.03)	39.64 [29.79]	11.92-106.61
RMSSD	Baseline	Total	42	46.24 (23.51)	41.02 [28.09]	15.82-106.67
RMSSD	Regular PBL	1	42	26.75 (13.61)	24.52 [19.38]	6.94-66.10
RMSSD	Regular PBL	2	42	28.83 (15.05)	26.92 [17.43]	12.04-79.19
RMSSD	Regular PBL	Total	42	27.79 (13.88)	25.99 [16.74]	10.50-67.78
RMSSD	PBL + Exam Simulation	1	42	21.66 (12.62)	19.67 [16.82]	5.19-53.70
RMSSD	PBL + Exam Simulation	2	42	23.53 (16.06)	23.79 [14.16]	4.24-85.99
RMSSD	PBL + Exam Simulation	Total	42	22.59 (13.81)	20.81 [15.69]	4.72-69.84
pNN50	Baseline	1	42	24.17 (19.38)	17.90 [33.24]	1.10-66.39
pNN50	Baseline	2	42	22.65 (18.13)	19.12 [33.06]	0.58-61.64
pNN50	Baseline	Total	42	23.41 (18.35)	19.09 [33.14]	1.09-64.02
pNN50	Regular PBL	1	42	7.76 (8.44)	4.58 [10.58]	0.00-31.66
pNN50	Regular PBL	2	42	9.96 (11.42)	6.90 [12.73]	0.20-43.10
pNN50	Regular PBL	Total	42	8.86 (9.54)	6.01 [11.45]	0.35-35.27
pNN50	PBL + Exam Simulation	1	42	5.40 (6.47)	3.36 [6.35]	0.00-25.74
pNN50	PBL + Exam Simulation	2	42	6.61 (10.13)	4.57 [6.46]	0.00-53.54
pNN50	PBL + Exam Simulation	Total	42	6.00 (8.00)	3.50 [6.72]	0.00-39.64
SDNN	Baseline	1	42	54.37 (19.35)	51.30 [29.60]	21.85-95.93
SDNN	Baseline	2	42	51.28 (16.77)	47.62 [22.33]	23.37-95.68
SDNN	Baseline	Total	42	52.82 (17.55)	48.72 [25.94]	22.61-93.02
SDNN	Regular PBL	1	42	39.05 (15.52)	36.53 [20.25]	14.74-75.83
SDNN	Regular PBL	2	42	41.22 (14.47)	38.14 [21.26]	19.40-79.43
SDNN	Regular PBL	Total	42	40.14 (14.40)	38.24 [22.33]	17.95-76.58
SDNN	PBL + Exam Simulation	1	42	34.63 (14.18)	32.17 [21.06]	13.98-76.71
SDNN	PBL + Exam Simulation	2	42	35.98 (14.54)	35.59 [18.64]	11.35-76.34
SDNN	PBL + Exam Simulation	Total	42	35.31 (13.81)	34.92 [20.45]	13.02-76.53
LF/HF ratio	Baseline	1	42	2.53 (2.46)	1.85 [2.42]	0.14-12.48
LF/HF ratio	Baseline	2	42	3.04 (2.76)	2.54 [3.01]	0.20-11.91
LF/HF ratio	Baseline	Total	42	2.78 (2.45)	2.31 [2.96]	0.36-12.20
LF/HF ratio	Regular PBL	1	42	3.93 (2.20)	3.66 [3.24]	1.04-8.64
LF/HF ratio	Regular PBL	2	42	4.19 (2.71)	3.77 [3.52]	0.87-12.41
LF/HF ratio	Regular PBL	Total	42	4.06 (2.24)	4.00 [2.88]	0.96-9.90
LF/HF ratio	PBL + Exam Simulation	1	42	4.83 (3.79)	3.80 [4.12]	0.94-23.32
LF/HF ratio	PBL + Exam Simulation	2	42	4.36 (2.57)	4.22 [3.42]	0.32-10.56
LF/HF ratio	PBL + Exam Simulation	Total	42	4.59 (2.80)	4.03 [3.17]	0.67-15.68

Note. Values are reported on the original metric for interpretability. RMSSD and SDNN are given in ms; pNN50 is given in percent; LF/HF ratio is unitless. Total values represent the mean of the two 5-minute intervals.

To describe condition-related change, within-person differences were defined as

$$\Delta_{E-R} = X_E - X_R$$

where X_E denotes the value in the examination-simulation condition and X_R the value in regular PBL. For the exploratory coupling analysis, additional RMSSD withdrawal was defined as

$$W_{RMSSD} = \ln(RMSSD_R) - \ln(RMSSD_E)$$

such that higher values indicate stronger additional vagally mediated HRV withdrawal during examination simulation relative to regular PBL.

Table 2. Descriptive statistics of psychological measures and post-session appraisal across regular PBL and PBL with peer-led examination simulation

Variable	Condition	Scale	n	M (SD)	Mdn [IQR]	Range
Social Interaction Anxiety (SIAS sum)	Pre / baseline trait	Sum score	42	44.95 (11.33)	44.00 [17.75]	24.00-66.00
Enjoyment	Regular PBL	Scale mean	42	2.37 (0.79)	2.25 [1.25]	1.00-4.00
Enjoyment	PBL + Exam Simulation	Scale mean	42	2.45 (0.74)	2.25 [1.00]	1.00-4.00
Anxiety	Regular PBL	Scale mean	42	1.52 (0.59)	1.38 [0.75]	1.00-3.25
Anxiety	PBL + Exam Simulation	Scale mean	42	2.00 (0.91)	2.00 [0.94]	1.00-5.00
State anxiety	Regular PBL	VAS	42	3.67 (2.67)	3.00 [5.00]	1.00-10.00
State anxiety	PBL + Exam Simulation	VAS	42	4.86 (2.50)	5.00 [4.00]	1.00-10.00
Boredom	Regular PBL	Scale mean	42	2.52 (0.96)	2.38 [1.19]	1.00-5.00
Boredom	PBL + Exam Simulation	Scale mean	42	2.35 (0.83)	2.12 [1.19]	1.00-4.50
State boredom	Regular PBL	VAS	42	4.14 (2.82)	4.00 [5.75]	1.00-10.00
State boredom	PBL + Exam Simulation	VAS	42	2.31 (1.81)	2.00 [1.75]	1.00-9.00
Motivation	Regular PBL	VAS	42	5.49 (2.10)	5.75 [2.88]	1.50-9.50
Motivation	PBL + Exam Simulation	VAS	42	5.86 (1.85)	6.00 [2.56]	2.25-9.50
Perceived stress	Regular PBL	VAS	42	4.62 (2.39)	5.00 [3.75]	1.00-10.00
Perceived stress	PBL + Exam Simulation	VAS	42	6.31 (2.28)	6.00 [3.00]	1.00-10.00
Self-confidence	Regular PBL	VAS	42	6.50 (2.12)	6.00 [3.00]	2.00-10.00
Self-confidence	PBL + Exam Simulation	VAS	42	5.67 (2.31)	5.00 [4.00]	1.00-10.00
Self-rated performance	Regular PBL	VAS	42	6.24 (1.72)	7.00 [2.00]	3.00-10.00
Self-rated performance	PBL + Exam Simulation	VAS	42	6.02 (1.76)	6.00 [2.00]	2.00-9.00
Benefited from Exam Format	Post only	1-5 response	42	3.71 (1.37)	4.00 [2.00]	1.00-5.00
Benefited from Regular Format	Post only	1-5 response	42	2.64 (1.25)	3.00 [1.00]	1.00-5.00
Exam Format preferred	Post only	1-5 response	42	3.60 (1.17)	4.00 [1.75]	1.00-5.00
Regular Format preferred	Post only	1-5 response	42	2.07 (1.18)	2.00 [2.00]	1.00-5.00
Exam Format was an adequate alternative	Post only	1-5 response	42	3.57 (1.25)	4.00 [2.00]	1.00-5.00

Note. Only variables reported in figures or model summaries are shown. Scale means are item means; VAS variables are visual analogue scale ratings; post-only items were rated from 1 to 5.

Peer-led examination simulation induced additional HRV withdrawal beyond regular PBL

Across total HRV values, both learning conditions were characterized by lower HRV relative to resting baseline. RMSSD decreased from baseline (M = 46.24 ms, SD = 23.51) to regular PBL (M = 27.79 ms, SD = 13.88) and was lowest during PBL with peer-led examination simulation (M = 22.59 ms, SD = 13.81). The same graded pattern was observed for SDNN, which decreased from baseline (M = 52.82 ms, SD = 17.55) to regular PBL (M = 40.14 ms, SD = 14.40) and was further reduced during examination simulation (M = 35.31 ms, SD = 13.81). pNN50 showed a comparable reduction from baseline (M = 23.41%, SD = 18.35) to regular PBL (M = 8.86%, SD = 9.54) and examination simulation (M = 6.00%, SD = 8.00). In contrast, LF/HF increased from baseline (M = 2.78, SD = 2.45) to regular PBL (M = 4.06, SD = 2.24) and examination simulation (M = 4.59, SD = 2.80), but showed no robust additional increase during examination simulation.

Paired within-person comparisons confirmed this autonomic response pattern. Log-RMSSD was lower during regular PBL than during baseline, Δ = -0.51, 95% CI [-0.61, -0.40], t(41) = -9.81, $p < .001$, dz = -1.51. Critically, log-RMSSD was further reduced during examination simulation compared with regular PBL, Δ = -0.27, 95% CI [-0.41, -0.13], t(41) = -3.89, $p < .001$, dz = -0.60. Log-SDNN showed the same condition effect, with lower values during examination simulation than during regular PBL, Δ = -0.15, 95% CI [-0.24, -0.05], t(41) = -3.10, p = .003, dz = -0.48. pNN50 was also lower during examination simulation than during regular PBL, Δ = -2.86 percentage points, 95% CI [-5.01, -0.71], t(41) = -2.69, p = .010, dz = -0.41. LF/HF increased from baseline to both learning conditions, but did not differ reliably between examination simulation and regular PBL, Δ = 0.09 on the log scale, t(41) = 0.96, p = .340.

To account for the interval-level structure of the physiological data, baseline-adjusted mixed-effects models were fitted for each HRV marker. The general model was

$$Y_{ij} = \beta_0 + \beta_1 E_{ij} + \beta_2 B_i + \beta_3 I_{ij} + u_i + \varepsilon_{ij}$$

where Y_{ij} denotes the standardized HRV outcome for participant (i) at interval (j), E_{ij} denotes the examination-simulation indicator, B_i denotes the corresponding resting baseline HRV value, I_{ij} denotes measurement interval, u_i is the participant-specific random intercept and ε_{ij} is the residual error term.

These interval-level models replicated the phase-level results. Examination simulation predicted lower standardized RMSSD, β = -0.448, 95% CI [-0.666, -0.230], p < .001, lower SDNN, β = -0.312, 95% CI [-0.540, -0.085], p = .007, and lower pNN50, β = -0.253, 95% CI [-0.491, -0.014], p = .038. There was no corresponding robust examination-simulation effect for LF/HF, β = 0.208, 95% CI [-0.083, 0.500], p = .161. Thus, peer-led examination simulation induced additional HRV withdrawal beyond the autonomic activation already present during regular PBL, with the clearest effects observed for RMSSD, SDNN, and pNN50 (Figure 1).

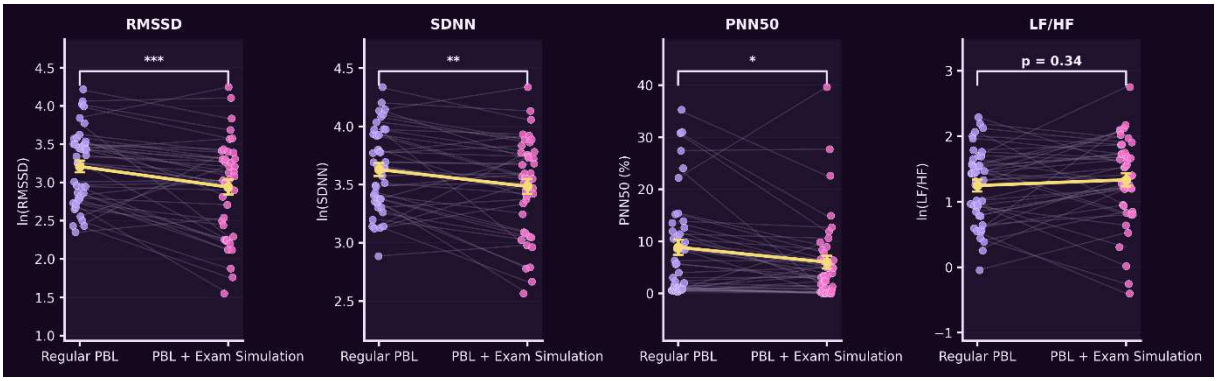

Figure 1. Heart rate variability response to peer-led examination simulation within problem-based learning. Paired within-person comparisons of HRV parameters during regular PBL and PBL with peer-led examination simulation. RMSSD, SDNN, and pNN50 were lower during the examination-simulation condition, indicating stronger vagally mediated HRV withdrawal and reduced overall variability during the assessment-like learning phase. LF/HF showed no reliable difference between conditions. Dots represent individual participants; connecting lines indicate within-person changes; group estimates are shown as mean values with confidence intervals.

Peer-led examination simulation shifted the achievement-emotional profile without reducing self-rated performance

The examination simulation produced a differentiated achievement-emotional response profile. Anxiety on the multi-item achievement-emotion scale increased from regular PBL (M = 1.52, SD = 0.59) to PBL with examination simulation (M = 2.00, SD = 0.91), $\Delta = 0.48$, 95% CI [0.23, 0.74], $t(41) = 3.81$, $p < .001$, $dz = 0.59$. State anxiety assessed by visual analogue scale also increased during examination simulation (M = 4.86, SD = 2.50) compared with regular PBL (M = 3.67, SD = 2.67), $\Delta = 1.19$, 95% CI [0.16, 2.22], $t(41) = 2.34$, $p = .024$, $dz = 0.36$. Perceived stress was higher during examination simulation (M = 6.31, SD = 2.28) than during regular PBL (M = 4.62, SD = 2.39), $\Delta = 1.69$, 95% CI [0.76, 2.63], $t(41) = 3.65$, $p < .001$, $dz = 0.56$.

In parallel, state boredom was lower during examination simulation (M = 2.31, SD = 1.81) than during regular PBL (M = 4.14, SD = 2.82), $\Delta = -1.83$, 95% CI [-2.83, -0.84], $t(41) = -3.71$, $p < .001$, $dz = -0.57$. Enjoyment and self-rated performance did not show reliable paired differences between conditions (all $p \geq .143$). Self-confidence was lower during examination simulation (M = 5.67, SD = 2.31) than during regular PBL (M = 6.50, SD = 2.12), $\Delta = -0.83$, 95% CI [-1.54, -0.12], $t(41) = -2.36$, $p = .023$, $dz = -0.36$.

Post-session appraisal favored the examination-simulation format. Students reported greater perceived benefit from the examination format (M = 3.71, SD = 1.37) than from the regular format (M = 2.64, SD = 1.25), mean difference = 1.07, 95% CI [0.57, 1.57], $t(41) = 4.30$, $p < .001$, $dz = 0.66$. They also preferred the examination format more strongly than the regular format (M = 3.60, SD = 1.17 vs. M = 2.07, SD = 1.18), mean difference = 1.52, 95% CI [0.88, 2.17], $t(41) = 4.79$, $p < .001$, $dz = 0.74$. The examination format was additionally rated as an adequate alternative to the regular format (M = 3.57, SD = 1.25). Together, these findings indicate that the examination simulation increased achievement-related anxiety and perceived stress while reducing boredom and preserving enjoyment and self-rated performance (Figure 2A, C).

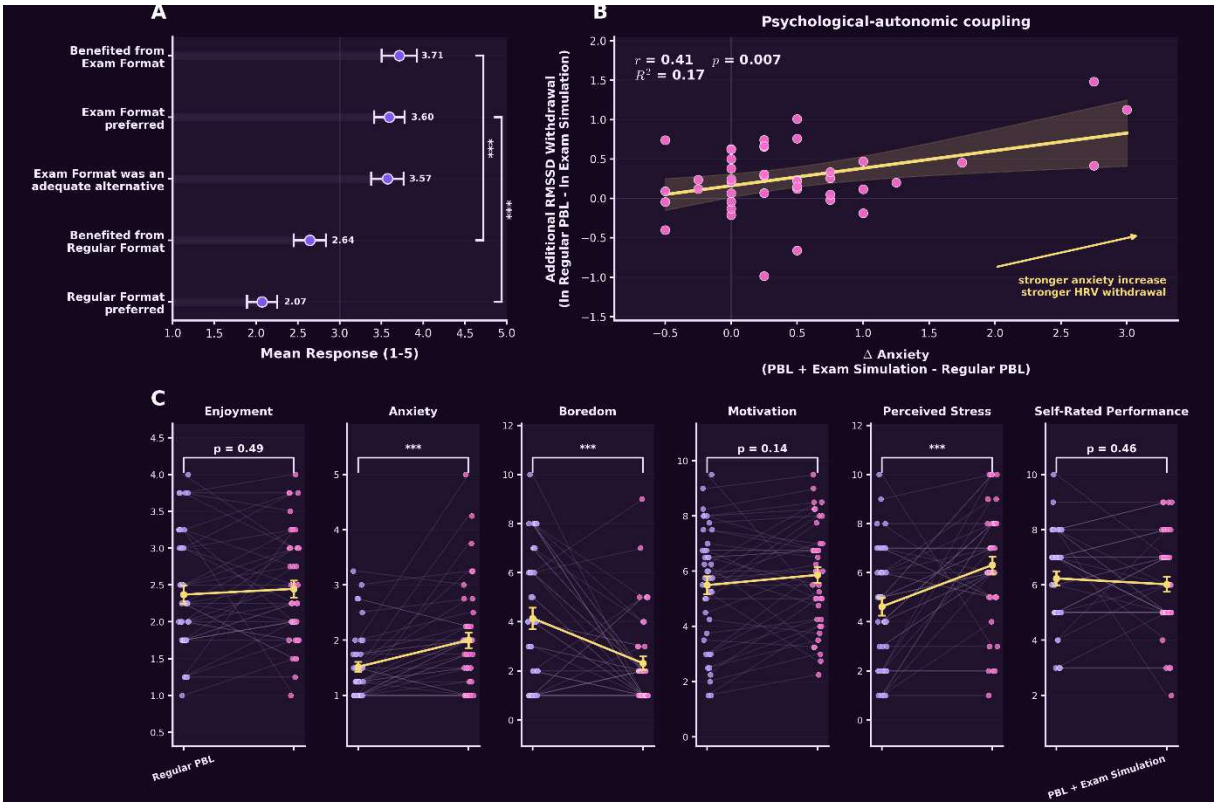

Figure 2. Educational appraisal, psychophysiological coupling and emotional response profile. A - Post-session appraisal of the regular PBL format and the PBL format with peer-led examination simulation. Students reported greater perceived benefit from, and stronger preference for, the examination-simulation format compared with the regular PBL format. B - Exploratory psychophysiological coupling between emotional activation and autonomic regulation. Stronger increases in anxiety from regular PBL to examination simulation were associated with stronger additional RMSSD withdrawal, suggesting convergence between subjective emotional activation and vagally mediated autonomic regulation. C - Within-person differences in learning-related emotional states between regular PBL and PBL with peer-led examination simulation.

Perceived stress showed anticipatory and in-situ activation but no sustained post-session elevation

Perceived stress ratings across the session provided a temporal manipulation check for the examination-simulation condition. Before the session, stress was already higher in the examination-simulation condition (M = 4.90, SD = 2.63) than before regular PBL (M = 3.02, SD = 2.23). During the intervention, stress increased to M = 6.33 (SD = 2.09) in the examination-simulation condition, compared with M = 3.95 (SD = 1.96) during regular PBL. After the session, stress ratings converged at low levels, with similar values after examination simulation (M = 2.33, SD = 1.22) and regular PBL (M = 2.48, SD = 1.71).

To model the temporal stress trajectory, perceived stress was analyzed using a categorical mixed-effects model:

$$S_{it} = \beta_0 + \beta_1 E_i + \beta_2 T_{t,during} + \beta_3 T_{t,post} + \beta_4 (E_i \times T_{t,during}) + \beta_5 (E_i \times T_{t,post}) + u_i + \varepsilon_{it}$$

where S_{it} denotes standardized perceived stress for participant i at time point t, E_i denotes the examination-simulation condition, T_{during} and T_{post} denote dummy indicators for the during-session and post-session time points, with pre-session serving as the reference category, u_i is the participant-specific random intercept, and ε_{it} is the residual error term.

The model reflected the descriptive stress profile. Examination simulation was associated with higher standardized stress at the pre-session reference point, β = 0.765, 95% CI [0.469, 1.062], $p < .001$. Stress increased from pre-session to intervention during regular PBL, β = 0.378, 95% CI [0.082, 0.674], $p = .012$. In the examination-simulation condition, stress showed a pronounced post-session reduction relative to its elevated pre-session level, condition × post-session β = -0.823, 95% CI [-1.242, -0.404], $p < .001$. SIAS did not reliably moderate the categorical stress trajectory terms (all interaction $p \geq .373$). Thus, the examination simulation elicited anticipatory and in-situ stress activation, but this activation did not persist after the session (Figure 3).

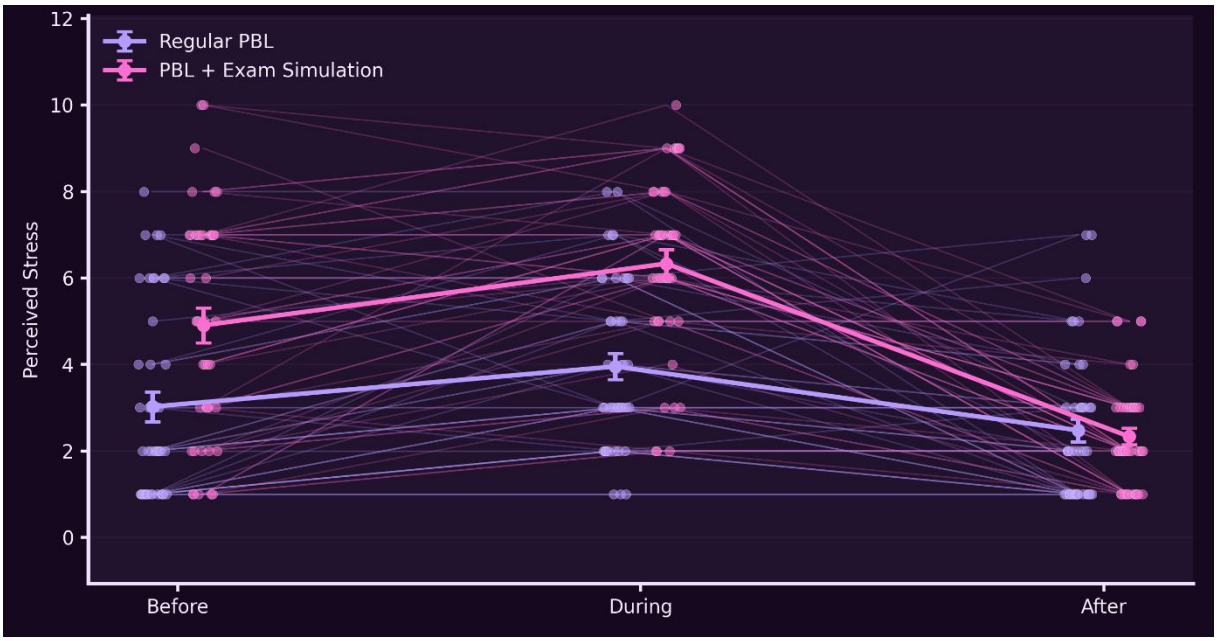

Figure 3. Temporal stress profile across regular PBL and peer-led examination simulation. Subjective stress ratings were assessed before, during, and after each learning condition. Points represent group means; error bars indicate variability estimates.

Social interaction anxiety marked psychological vulnerability but did not substantially moderate the examination-simulation effect

Exploratory mixed models were used to examine whether social interaction anxiety shaped students' responses to peer-led examination simulation. For standardized psychological outcomes, the core model was

$$Y_{ij} = \beta_0 + \beta_1 E_{ij} + \beta_2 SIAS_{z,i} + \beta_3 (E_{ij} \times SIAS_{z,i}) + u_i + \varepsilon_{ij}$$

where Y_{ij} denotes the standardized psychological outcome for participant i at observation j, E_{ij} denotes the examination-simulation indicator, $SIAS_{z,i}$ denotes the standardized SIAS score of participant i, u_i is the participant-specific random intercept, and ε_{ij} is the residual error term.

Across models, examination simulation remained a robust predictor of higher perceived stress and anxiety. In the perceived-stress model, which additionally adjusted for RMSSD change from baseline, examination simulation predicted higher standardized stress, β = 0.748, SE =

0.195, 95% CI [0.365, 1.131], $p < .001$. SIAS also predicted higher stress, $\beta = 0.307$, SE = 0.138, 95% CI [0.037, 0.577], $p = .026$, whereas the condition × SIAS interaction was negligible, $\beta = -0.037$, $p = .841$. RMSSD change from baseline was not a reliable main-effect predictor in this model, $\beta = 0.103$, $p = .318$.

The same pattern was observed for anxiety-related outcomes. Examination simulation predicted higher standardized anxiety on the achievement-emotion scale, $\beta = 0.602$, 95% CI [0.296, 0.907], $p < .001$, and higher state anxiety, $\beta = 0.450$, 95% CI [0.078, 0.822], $p = .018$. SIAS was associated with higher state anxiety, $\beta = 0.370$, 95% CI [0.094, 0.646], $p = .009$, and with lower self-confidence, $\beta = -0.491$, 95% CI [-0.747, -0.235], $p < .001$. Examination simulation also predicted lower self-confidence, $\beta = -0.371$, 95% CI [-0.675, -0.067], $p = .017$.

For autonomic regulation, examination simulation predicted lower standardized log-RMSSD, $\beta = -0.469$, 95% CI [-0.702, -0.236], $p < .001$. Neither SIAS, $\beta = 0.207$, $p = .158$, nor the condition × SIAS interaction, $\beta = 0.034$, $p = .777$, explained additional RMSSD variance. Across outcomes, SIAS therefore appeared to function primarily as a general psychological vulnerability marker rather than as a strong moderator of the examination-simulation effect. The model-based estimates are summarized in Table 3.

Table 3. Model-based estimates of the emotional and autonomic response profile induced by peer-led examination simulation.

Analysis / outcome	Key predictor	Estimate	SE	95% CI	p value	Interpretation
Perceived stress	condition_exam	β = 0.748	0.195	[0.365, 1.131]	p < .001	Exam simulation predicted higher perceived stress.
	SIAS_z	β = 0.307	0.138	[0.037, 0.577]	p = .026	Higher SIAS predicted generally higher stress.
	condition_exam × SIAS_z	β = -0.037	0.187	[-0.404, 0.329]	p = .841	SIAS did not moderate the stress effect.
Anxiety	condition_exam	β = 0.602	0.156	[0.296, 0.907]	p < .001	Exam simulation predicted higher anxiety.
	SIAS_z	β = 0.325	0.139	[0.052, 0.598]	p = .020	Higher SIAS predicted generally higher anxiety.
	condition_exam × SIAS_z	β = -0.009	0.158	[-0.318, 0.301]	p = .955	SIAS did not amplify the exam effect.
Self-confidence	condition_exam	β = -0.371	0.155	[-0.675, -0.067]	p = .017	Exam simulation predicted lower self-confidence.
	SIAS_z	β = -0.491	0.131	[-0.747, -0.235]	p < .001	Higher SIAS predicted lower self-confidence.
RMSSD	condition_exam	β = -0.469	0.119	[-0.702, -0.236]	p < .001	Exam simulation predicted lower RMSSD.
	condition_exam × SIAS_z	β = 0.034	0.120	[-0.202, 0.270]	p = .777	SIAS did not moderate RMSSD differences.
Psychophysiological coupling	condition_exam × RMSSD_change_z	β = 0.477	0.207	[0.071, 0.884]	p = .021	Stress-RMSSD coupling differed between conditions.

Note. Estimates are standardized fixed effects from mixed-effects models with participant-specific random intercepts. condition_exam was coded 0 = regular PBL and 1 = PBL with peer-led examination simulation. SIAS_z denotes standardized Social Interaction Anxiety Scale score. RMSSD_change_z denotes standardized RMSSD change from baseline. CI = confidence interval.

Anxiety increases were coupled with additional RMSSD withdrawal

Exploratory psychophysiological coupling analyses tested whether stronger achievement-emotional activation was associated with stronger autonomic withdrawal during examination simulation. The primary coupling analysis related the change in achievement-related anxiety to additional RMSSD withdrawal:

$$W_{RMSSD} = \alpha + \beta \Delta_{Anxiety} + \varepsilon$$

Participants with larger increases in anxiety from regular PBL to examination simulation showed stronger additional RMSSD withdrawal, $r = .41$, $p = .007$, $R^2 = .17$. In the corresponding simple regression, each one-point increase in Δ-anxiety was associated with an additional 0.22 log-unit shift in RMSSD withdrawal. This association is shown in Figure 2B.

A complementary mixed model further examined whether the association between perceived stress and RMSSD change differed by condition:

$$S_{ij} = \beta_0 + \beta_1 E_{ij} + \beta_2 SIAS_{z,i} + \beta_3 C_{ij}^{z} + \beta_4 \left(E_{ij} \times C_{ij}^{z}\right) + u_i + \varepsilon_{ij}$$

where S_{ij} denotes standardized perceived stress and C_{ij}^{z} denotes standardized RMSSD change from baseline. The condition × RMSSD-change term was positive, β = 0.477, SE = 0.207, 95% CI [0.071, 0.884], p = .021, indicating that the stress-RMSSD association differed between regular PBL and examination simulation. Because these analyses were exploratory, they should be interpreted as evidence for partial psychophysiological convergence rather than as confirmatory tests of causal coupling. Overall, the coupling findings suggest that the examination-simulation condition linked subjective achievement-emotional activation with vagally mediated autonomic regulation.

Discussion

Principal findings

The present study shows that embedding a peer-led examination simulation into a regular PBL session produced a distinct psychophysiological and emotional activation profile. Compared with regular PBL, the examination-simulation condition was associated with stronger reductions in HRV, reflected by lower RMSSD, SDNN, and pNN50 values, whereas LF/HF did not differ reliably between the two learning conditions. This pattern was replicated in interval-level mixed models adjusting for baseline HRV and measurement interval, supporting the robustness of the examination-simulation effect for vagally mediated and overall HRV indices. Psychologically, the simulation condition elicited higher state anxiety and perceived stress, while boredom was lower. Importantly, enjoyment, and self-rated performance did not show reliable decreases, indicating that the simulation did not produce a broadly negative motivational response. Students additionally reported greater perceived benefit from and stronger preference for the examination format compared with the regular PBL format.

Peer-led examination simulation as a salience-enhancing extension of PBL

Problem-based learning is commonly conceptualized as a learning environment that promotes active knowledge construction, self-directed inquiry, collaborative reasoning, and contextualized application rather than passive reception of information[3]. However, prior work has also emphasized that the educational effectiveness of PBL depends on the quality of its implementation and on whether the learning environment actually activates the cognitive, social, and motivational processes it is intended to stimulate[8]. Against this background, the present findings suggest that peer-led examination simulation may function as a salience-enhancing extension of PBL. By introducing an assessment-like but still formative and student-led element, the simulation shifted the PBL episode from collaborative knowledge exchange alone toward a more performance-relevant context requiring active retrieval, explanation, and defense of knowledge. This interpretation is consistent with assessment-for-learning frameworks, in which assessment-like activities are used to guide and stimulate learning rather than merely to certify performance[29], and with retrieval-based learning research showing that active recall can strengthen learning more effectively than repeated exposure or passive review[30].

Autonomic activation: HRV withdrawal as task-related mobilization

The HRV profile suggests that peer-led examination simulation increased autonomic mobilization beyond the activation induced by regular PBL. Both learning conditions were characterized by lower HRV relative to baseline, consistent with evidence that HRV provides a peripheral window into mental workload and regulatory effort during cognitively demanding tasks[31,32]. Thus, PBL itself appeared to constitute an active physiological learning state rather

than a neutral instructional condition. Critically, RMSSD, SDNN, and pNN50 were further reduced during examination simulation compared with regular PBL, and these effects were replicated in interval-level mixed models controlling for baseline HRV and measurement interval. Thus, the simulation effect cannot be reduced to stable individual differences in resting autonomic regulation, but reflects a condition-specific shift in autonomic state. Lower RMSSD and pNN50 indicate stronger withdrawal of vagally mediated HRV, whereas lower SDNN points to reduced overall variability during the assessment-like performance phase[33–36]. Within the neurovisceral integration framework, transient vagal withdrawal can be interpreted as a state-dependent adjustment of an integrated central-autonomic regulatory network connecting prefrontal and limbic control regions with vagal and sympathetic outputs to the heart[37]. In the present context, the additional reduction in vagally mediated HRV during peer-led examination simulation may therefore index the mobilization of attentional, affective, and social-evaluative regulatory resources required to retrieve, organize, and defend knowledge in an assessment-like peer setting, rather than maladaptive stress per se. This interpretation is further supported by the hierarchical extension of the neurovisceral integration model, which conceptualizes cardiac vagal control as the output of a multi-level control architecture integrating brainstem, limbic, interoceptive, and prefrontal systems. Within this framework, higher levels of the hierarchy do not merely respond to current bodily demands, but integrate exteroceptive information, memory, conceptual appraisal, and current goals to regulate autonomic output in anticipation of expected cognitive and social-emotional demands[38]. Thus, the HRV withdrawal observed during the simulation may reflect a state-dependent adjustment of this central-autonomic hierarchy to the predicted and ongoing demands of an assessment-like learning episode.

Achievement emotions: higher anxiety, lower boredom, stable motivation and self-rated performance

Achievement-emotion theory conceptualizes learning-related emotions not as peripheral reactions to instruction, but as state variables that shape attention, motivation, cognitive resources, self-regulated learning, and performance-related behavior[11]. Within this framework, emotions differ not only in valence, but also in their activating or deactivating quality. This distinction is important for interpreting the present findings. The peer-led examination simulation increased anxiety and perceived stress compared with regular PBL, indicating that the added assessment-like element raised the emotional demand and perceived situational relevance of the learning episode. However, the increase in activating negative emotion did not generalize to a broad deterioration of motivational appraisal, as enjoyment, motivation, and self-rated performance remained statistically stable. At the same time, boredom was reduced, which is relevant because achievement-related boredom is conceptualized as a deactivating emotion arising from low control–value appraisals and has been associated with attention problems, reduced intrinsic motivation, lower effort, weaker elaboration and self-regulation, and poorer academic performance[9,39]. This emotional shift was accompanied by lower RMSSD, pNN50, and SDNN, indicating reduced parasympathetically mediated and overall HRV during the examination-simulation condition. The convergence of reduced boredom and stronger autonomic mobilization suggests that the simulation increased the salience and regulatory demands of the PBL episode, rather than merely inducing nonspecific distress. Thus, the observed profile supports an interpretation of peer-led examination simulation as a calibrated activation of the learning state: emotionally and physiologically more mobilizing than regular PBL, but not motivationally disruptive.

Psychophysiological coupling and individual susceptibility

The exploratory coupling analyses indicate partial psychophysiological convergence during peer-led examination simulation: stronger increases in anxiety were associated with stronger

additional RMSSD withdrawal. This suggests that vagal withdrawal was not merely a nonspecific physiological response, but was linked to learners' subjective appraisal of the assessment-like situation. Conceptually, this aligns with models of HRV as a marker of stress-related regulatory effort and integrated cognitive-affective control[36,38,40–42]. At the same time, social interaction anxiety showed a selective susceptibility pattern. SIAS predicted higher state anxiety and lower self-confidence, but did not robustly moderate stress ratings, RMSSD, or the temporal stress trajectory. Thus, the simulation appears to have elicited a broadly shared autonomic activation response, while socially more anxious students showed greater vulnerability at the level of subjective appraisal. This distinction is consistent with recent work emphasizing individual variability in subjective–physiological coupling and HRV dynamics during social-evaluative stress[43].

Limitations

Future studies should extend the present repeated-measures design toward real-time, event-triggered psychophysiological datasets in which continuous biosignals are synchronized with time-stamped annotations of discrete instructional events. Although the current findings show additional HRV withdrawal and emotional activation during peer-led examination simulation, predefined 5-minute intervals cannot resolve the temporal coupling of autonomic regulation with specific learning events. Real-time approaches could align physiological dynamics with anticipatory waiting, question onset, active retrieval, explanation, peer evaluation, feedback, and recovery, thereby separating anticipatory arousal, retrieval-related regulatory effort, and post-performance downregulation. Future designs should also incorporate complementary physiological markers, including respiratory rate and tidal patterns to control for respiration-dependent HRV effects, as well as sympathetic or arousal-sensitive indices such as electrodermal activity, pre-ejection period, peripheral temperature, or pupillometry. Such

multimodal recordings would allow a more differentiated decomposition of parasympathetic withdrawal, sympathetic activation, respiratory modulation, and cognitive-affective workload. Building on hierarchical neurovisceral models, these real-time indicators, combined with speech, behavior, and brief state ratings, could be used to calibrate simulation intensity and feedback timing to the learner's current regulatory state. This would shift psychophysiological measurement from retrospective state characterization toward adaptive, event-sensitive educational intervention design.

Conclusion

The present study provides evidence that peer-led examination simulation can meaningfully reshape the psychophysiological and emotional state profile of PBL. By combining repeated-measures HRV assessment, psychological state measures, post-session appraisal, and baseline-adjusted mixed models, the study demonstrates that the examination simulation elicited a coherent activation pattern across autonomic, emotional, and evaluative domains. Compared with regular PBL, the simulation induced additional vagally mediated HRV withdrawal, higher anxiety and perceived stress, and lower boredom, while enjoyment, and self-rated performance remained stable. At the same time, students reported greater perceived benefit from, and stronger preference for, the examination format. This convergence indicates that the intervention did not merely add stress to PBL, but shifted the learning episode toward a more salient, assessment-like, and educationally valued state. More broadly, these findings support the use of psychophysiological measurement to examine how instructional design modulates attention, emotion, and autonomic regulation during authentic medical learning.

Acknowledgements

We would like to express our sincere gratitude to all student participants who took part in this study. Their willingness to engage in the regular PBL sessions, the peer-led examination simulation, the psychological assessments, and the physiological measurements made this research possible. The authors would like to thank Dr. Matthias Joswig and Nina Porsch for their valuable support in the organization and conduct of data collection. Finally, we thank Juliane Cramer for her valuable assistance as a student research assistant in supporting the organizational and practical implementation of the study.

Ethics Approval declaration

This research was conducted in accordance with the principles outlined in the Declaration of Helsinki. Approval for the study was obtained from the *Ethics Committee of the Professional School of Education* at Ruhr University Bochum (Reference No. EPSE-2022-004, dated 12.09.2022). The study adhered to all ethical guidelines to ensure the safety, well-being, and confidentiality of all participants.

Funding Declaration

This research did not receive funding.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 5.5 in order to enhance the readability and language of this work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

1. Barrows, H. S. & Tamblyn, R. M. *Problem-Based Learning: An Approach to Medical Education*. (Springer Publishing Company, 1980).

2. Barrows, H. S. Problem-based learning in medicine and beyond: A brief overview. *New Directions for Teaching and Learning* **1996**, 3–12 (1996).

3. Hmelo-Silver, C. E. Problem-Based Learning: What and How Do Students Learn? *Educ. Psychol. Rev.* **16**, 235–266 (2004).

4. Trullàs, J. C., Blay, C., Sarri, E. & Pujol, R. Effectiveness of problem-based learning methodology in undergraduate medical education: a scoping review. *BMC Med. Educ.* **22**, 104 (2022).

5. Koh, G. C.-H., Khoo, H. E., Wong, M. L. & Koh, D. The effects of problem-based learning during medical school on physician competency: a systematic review. *Can. Med. Assoc. J.* **178**, 34–41 (2008).

6. Bodagh, N., Bloomfield, J., Birch, P. & Ricketts, W. Problem-based learning: a review. *Br. J. Hosp. Med.* **78**, C167–C170 (2017).

7. Dwidmuthe, S., Dubhashi, S., Pusdekar, V., Tiwari, V. & Sahoo, S. Insight into "Problem-based Learning" in Medical Education – Students' Perceptions about its Facilitators and Barriers: A Cross-sectional Study. *Ann. Afr. Med.* **24**, 350–355 (2025).

8. Dolmans, D. H. J. M., De Grave, W., Wolfhagen, I. H. A. P. & Van Der Vleuten, C. P. M. Problem-based learning: future challenges for educational practice and research. *Med. Educ.* **39**, 732–741 (2005).

9. Pekrun, R. The Control-Value Theory of Achievement Emotions: Assumptions, Corollaries, and Implications for Educational Research and Practice. *Educ. Psychol. Rev.* **18**, 315–341 (2006).

10. Gellisch, M. *et al.* Rethinking Learning Experience: How Generally Perceived Life Stress Influences Students' Course Perceptions in Different Learning Environments. *Eur. J. Investig. Health Psychol. Educ.* **13**, 1491–1504 (2023).

11. Pekrun, R., Goetz, T., Titz, W. & Perry, R. P. Academic Emotions in Students' Self-Regulated Learning and Achievement: A Program of Qualitative and Quantitative Research. *Educ. Psychol.* **37**, 91–105 (2002).

12. Mega, C., Ronconi, L. & De Beni, R. What makes a good student? How emotions, self-regulated learning, and motivation contribute to academic achievement. *J. Educ. Psychol.* **106**, 121–131 (2014).

13. Preuß, D., Schoofs, D., Schlotz, W. & Wolf, O. T. The stressed student: Influence of written examinations and oral presentations on salivary cortisol concentrations in university students. *Stress* **13**, 221–229 (2010).

14. Gellisch, M. *et al.* Decreased sympathetic cardiovascular influences and hormone-physiological changes in response to Covid-19-related adaptations under different learning environments. *Anat. Sci. Educ.* **15**, 811–826 (2022).

15. Bierbrauer, A., Fellner, M.-C., Heinen, R., Wolf, O. T. & Axmacher, N. The memory trace of a stressful episode. *Current Biology* **31**, 5204-5213.e8 (2021).

16. Gellisch, M., Bablok, M., Brand-Saberi, B. & Schäfer, T. Neurobiological stress markers in educational research: A systematic review of physiological insights in health science education. *Trends Neurosci. Educ.* **37**, 100242 (2024).

17. Taelman, J., Vandeput, S., Spaepen, A. & Van Huffel, S. Influence of Mental Stress on Heart Rate and Heart Rate Variability. in 1366–1369 (2009). doi:10.1007/978-3-540-89208-3_324.

18. Shaffer, F. & Ginsberg, J. P. An Overview of Heart Rate Variability Metrics and Norms. *Front. Public Health* **5**, (2017).

19. Yerkes, R. M. & Dodson, J. D. The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology* **18**, 459–482 (1908).

20. Vogel, S. & Schwabe, L. Learning and memory under stress: implications for the classroom. *NPJ Sci. Learn.* **1**, 16011 (2016).

21. Sandi, C. & Pinelo-Nava, M. T. Stress and memory: behavioral effects and neurobiological mechanisms. *Neural Plast.* **2007**, 78970 (2007).

22. Gellisch, M., Bablok, M., Morosan-Puopolo, G., Schäfer, T. & Brand-Saberi, B. Autonomic stress responses in oral examination simulations: Neuroscientific insights from comparing peer-led and lecturer-led approaches. *Trends Neurosci. Educ.* **40**, 100270 (2025).

23. Schaffarczyk, M., Rogers, B., Reer, R. & Gronwald, T. Validity of the Polar H10 Sensor for Heart Rate Variability Analysis during Resting State and Incremental Exercise in Recreational Men and Women. *Sensors* **22**, 6536 (2022).

24. Malik, M. Heart Rate Variability - Standards of Measurement, Physiological Interpretation, and Clinical Use: Task Force of The European Society of Cardiology and the North American Society for Pacing and Electrophysiology. *Annals of Noninvasive Electrocardiology* **1**, 151–181 (1996).

25. Mattick, R. P. & Clarke, J. C. Development and validation of measures of social phobia scrutiny fear and social interaction anxiety. *Behaviour Research and Therapy* **36**, 455–470 (1998).

26. Pekrun, R., Goetz, T., Frenzel, A. C., Barchfeld, P. & Perry, R. P. Measuring emotions in students' learning and performance: The Achievement Emotions Questionnaire (AEQ). *Contemp. Educ. Psychol.* **36**, 36–48 (2011).

27. Yeung, A. W. K. & Wong, N. S. M. The Historical Roots of Visual Analog Scale in Psychology as Revealed by Reference Publication Year Spectroscopy. *Front. Hum. Neurosci.* **13**, (2019).

28. Lavedán Santamaría, A. *et al.* Diagnostic Concordance between the Visual Analogue Anxiety Scale (VAS-A) and the State-Trait Anxiety Inventory (STAI) in Nursing Students during the COVID-19 Pandemic. *Int. J. Environ. Res. Public Health* **19**, 7053 (2022).

29. Schuwirth, L. W. T. & Van der Vleuten, C. P. M. Programmatic assessment: From assessment of learning to assessment for learning. *Med. Teach.* **33**, 478–485 (2011).

30. Roediger, H. L. & Karpicke, J. D. Test-Enhanced Learning. *Psychol. Sci.* **17**, 249–255 (2006).

31. Delliaux, S., Delaforge, A., Deharo, J.-C. & Chaumet, G. Mental Workload Alters Heart Rate Variability, Lowering Non-linear Dynamics. *Front. Physiol.* **10**, (2019).

32. Gellisch, M. *et al.* Interactive teaching enhances students' physiological arousal during online learning. *Annals of Anatomy - Anatomischer Anzeiger* **247**, 152050 (2023).

33. Shaffer, F. & Ginsberg, J. P. An Overview of Heart Rate Variability Metrics and Norms. *Front. Public Health* **5**, (2017).

34. Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J. & Wager, T. D. A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neurosci. Biobehav. Rev.* **36**, 747–756 (2012).

35. Massaro, S. & Pecchia, L. Heart Rate Variability (HRV) Analysis: A Methodology for Organizational Neuroscience. *Organ. Res. Methods* **22**, 354–393 (2019).

36. Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H. & Koo, B.-H. Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. *Psychiatry Investig.* **15**, 235–245 (2018).

37. Thayer, J. F. & Lane, R. D. A model of neurovisceral integration in emotion regulation and dysregulation. *J. Affect. Disord.* **61**, 201–216 (2000).

38. Smith, R., Thayer, J. F., Khalsa, S. S. & Lane, R. D. The hierarchical basis of neurovisceral integration. *Neurosci. Biobehav. Rev.* **75**, 274–296 (2017).

39. Pekrun, R., Goetz, T., Daniels, L. M., Stupnisky, R. H. & Perry, R. P. Boredom in achievement settings: Exploring control–value antecedents and performance outcomes of a neglected emotion. *J. Educ. Psychol.* **102**, 531–549 (2010).

40. Yoo, H. H., Yune, S. J., Im, S. J., Kam, B. S. & Lee, S. Y. Heart Rate Variability-Measured Stress and Academic Achievement in Medical Students. *Medical Principles and Practice* **30**, 193–200 (2021).

41. Hjortskov, N. *et al.* The effect of mental stress on heart rate variability and blood pressure during computer work. *Eur. J. Appl. Physiol.* **92**, 84–89 (2004).

42. Held, J., Vîslă, A., Wolfer, C., Messerli-Bürgy, N. & Flückiger, C. Heart rate variability change during a stressful cognitive task in individuals with anxiety and control participants. *BMC Psychol.* **9**, 44 (2021).

43. Sommerfeldt, S. L., Schaefer, S. M., Brauer, M., Ryff, C. D. & Davidson, R. J. Individual Differences in the Association Between Subjective Stress and Heart Rate Are Related to Psychological and Physical Well-Being. *Psychol. Sci.* **30**, 1016–1029 (2019).