

Inquiry-induced Stress? Physiological Stress Levels of Lower Secondary School Students in Inquiry-based Situations in Science Classes

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ABSTRACT

In recent years, psychological strain among young people has increased worldwide due to numerous social crises. School and classroom performance requirements are primary sources of stress for students. Classroom stress emerges when the demands of a teaching situation surpass personal resources, such as self-efficacy beliefs (SEB). Scientific inquiry-based activities, including experiments or modeling, pose a significant challenge in science lessons because students have limited resources in this area, even by the end of lower secondary school. Consequently, an elevated stress level is anticipated in such situations. This exploratory study examined secondary school students' heart rate variability ($n = 86$ valid data sets), an indicator of physiological stress, during inquiry-based and non-inquiry-based (communication) situations in science lessons. Moreover, a hierarchical cluster analysis was conducted to investigate whether stress levels differed as a function of individual dispositions that encompassed both stress levels and scientific SEBs. Overall, no significantly elevated stress level was observed during inquiry-based situations. Nevertheless, three types of students with different physiological stress responses were identified, suggesting that individual dispositions are pivotal in guiding personalized stress prevention in science lessons.

KEY WORDS: Heart rate variability; inquiry-based learning; physiological stress; science teaching; self-efficacy beliefs

INTRODUCTION

In recent years, multiple social crises have substantially increased psychological stress among schoolchildren (Schmitz et al., 2024). In addition to concerns about the future, one's own health, the well-being of close relatives, meeting societal expectations, problems in social relationships (Núñez-Regueiro and Núñez-Regueiro, 2021), and a decline in social support from parents and peers (Badura et al., 2024), school is considered a primary source of stress for young people (Seiffge-Krenke, 2021). This is because students are subject to an increasing number of school-related stressors (Whiting et al., 2021). These stressors encompass school transitions, exam anxiety, student rivalries and aggression (Seiffge-Krenke, 2008), bullying by classmates, unsatisfactory teacher-student relationships (Núñez-Regueiro and Núñez-Regueiro, 2021), personal performance expectations (Knittel et al., 2015), and increased pressure to perform well in class (Robert Bosch Stiftung, 2024). Consequently, 40 % of students in Germany experience severe school-related stress (Hansen et al., 2023). Nevertheless, as numerous studies on the mental health of schoolchildren from various countries demonstrate, it is a global challenge (e.g., Badura et al., 2024; Martínez-Líbano and Yeomans-Cabrera, 2024; Willis et al., 2021). According to the transactional stress model (Lazarus and Folkman, 1984), stress arises when students perceive that situational demands exceed their personal resources (Reif and Spieß, 2018b).

In Germany, the educational standards delineate the skills students should attain by the end of lower secondary school. In biology, students should develop content knowledge and evaluative competence, along with inquiry (e.g., experimentation and modeling) and communication skills (KMK, 2024). Explicitly, the complex challenges involved in scientific inquiry-based processes pose a potential source of stress, because they entail high cognitive loads and increased failure risks (Minkley et al., 2017). The complexity of scientific inquiry-based teaching situations arises from their dual function: On the one hand, students must learn practical scientific methods, and on the other, they must acquire a theoretical understanding of science and its epistemological nature (Webersen and Riese, 2025). Approximately 40 percent of students in Germany do not meet the educational standards for inquiry-based work (Stanat et al., 2019; Lewalter et al., 2023; KMK, 2024), suggesting inadequate individual resources in this domain. One can distinguish two types of resources. External resources are provided by the situation itself (e.g., support from classmates or teachers, or helpful teaching materials), while internal resources depend on the person's traits (e.g., students' competencies or self-efficacy beliefs [SEB]) (Wendland and Jansen, 2018). SEB assesses one's ability to take the necessary measures to navigate a situation (Bandura, 2002). As an internal resource, SEB can thus notably impact situation assessment and stress management (Satow and

Bäßler, 1998), even in inquiry-based and communication situations in science classes.

Lower secondary school students exhibit various coping strategies, such as using humor, engaging in physical or passive activities (e.g., sports, playing video games, eating, or sleeping), seeking familial support, participating in social activities, externalizing feelings (e.g., blaming others), or developing proactive orientations (Copeland and Hess, 1995; Hess and Copeland, 2001). Nonetheless, most young people's stress management is less problem-oriented and more emotional (TK, 2021). Hence, it hardly addresses the actual stressors sustainably. When coping strategies are ineffective or inadequate, stress reactions are emotionally and physiologically noticeable (Reif & Spieß, 2018b). Stress impacts the frequency and variability of heartbeats (Kim et al., 2018), the level of the stress hormone cortisol in body fluids (Bozovic et al., 2013), and electrodermal activity (skin conductance; Boucsein, 1988). One can also detect mental stress at the molecular level by measuring specific microRNAs to assess stress-related gene activity (Krammer et al., 2023). Furthermore, school stress seriously influences students' overall life satisfaction (Grasaas et al., 2024), their educational success, and health (Bäuerle and Kury, 1980; Hoferichter and Raufelder, 2022; OECD, 2017). Chronic school-related stress can lead to burnout symptoms among students (Hoferichter et al., 2023). Therefore, a clear need for preventive measures in schools is evident (Reiß et al., 2023).

Effective stress prevention in science education involves specifying the primary sources of stress. However, to date, only a few studies have explored the effects of individual interventions on students' physiological stress in science class (Minkley et al., 2017; Minkley et al., 2018; Minkley et al., 2024). Accordingly, assessing the specific stress potential of inquiry-based teaching situations compared to other teaching situations is impossible. To this end, our study focuses on this research gap.

METHODOLOGY

In an exploratory field study, we measured the heart rate variability ([HRV], a physiological measure of the current stress level; Kim et al., 2018) of lower secondary school students at comprehensive schools in Germany ($n = 112$, of which $n = 86$ data sets were evaluable, average age = 13.0) during a rest period and a subsequent science lesson. Participation was voluntary. As all participants were under 18, written informed consent was obtained from their parents or legal guardians before participation. Classes typically lasted 90 min. We aimed to determine students' physiological stress levels during teaching situations involving inquiry-based and/or non-inquiry-based activities (i.e., communication unrelated to inquiry-based activities). HRV testing is an established method of evaluating individual stress (Kim et al., 2018). It can yield meaningful insights into learner stress during educational activities (Kim et al., 2024). The interaction between the

sympathetic nervous system (SN) and the parasympathetic nervous system (PN) causes fluctuations in the interval length between heartbeats (i.e., HRV). During relaxation, PN activity dominates, elevating HRV. However, in stressful situations, SN activity predominates, diminishing HRV (Zetterman et al., 2023). HRV was continuously detected and recorded as a time series of RR intervals (the time between two heartbeats) using a chest-strap-based monitoring system (Firstbeat Sports, Firstbeat Technologies Oy, Finland; e.g., Jin et al., 2022; Conte et al., 2025). This method offers greater relative freedom from interference for test subjects than measuring other biomarkers (e.g., cortisol in saliva or blood). The data quality of mobile chest strap sensors is comparable to that of wired electrocardiograms (Sammuto et al., 2011). In addition, continuous HRV recording addresses potential cognitive bias issues that can arise with retrospective questionnaires (Stone and Shiffman, 2002).

Before the lesson, the students sat quietly at their desks for 5 min and listened to a relaxing guided imagery story. This type of story can facilitate relaxation by activating the PN (Wehrle, 2011). As an exploratory field study in regular classroom instruction, the content of subsequent science lessons differed. The teaching situations were categorized into inquiry-based situations (applying scientific working techniques, observing, comparing, classifying, planning, conducting, and evaluating experiments, as well as modeling) and communication situations distinguishable from inquiry-based activities (e.g., accessing, processing, and exchanging information, arguing) based on the competency descriptions of the German educational standards (KMK, 2024). The start and end times of each teaching situation were recorded on an observation sheet to calculate HRV for each situation. Individual assignment in the teaching situation was achieved by attaching a number label to each student's clothing.

Using Kubios HRV software (Kubios Oy, Finland; Tarvainen et al., 2014), we first visually inspected measurements for low signal quality, automatically identified noisy signal segments, and performed automatic artifact correction. We discarded low-quality measurements (Eronen et al., 2024), so that we ultimately encompassed the RR time series of $n = 86$ students in the final assessment. The RR time series were adjusted for very low-frequency trends using the smoothness-prior method (Tarvainen et al., 2002) to prevent further analyses from being impacted by slow heart rate changes (below 0.04 Hz) over the evaluation period. HRV was calculated exclusively for teaching situations lasting ≥ 5 min, aligning with typical short-term HRV measurements (Camm et al., 1996). Consistent with comparable studies (e.g., Minkley et al., 2017), teaching situations lasting at least 10 min were divided into two or more consecutive 5-min intervals. The Baevsky stress index (SI) (Brisinda et al., 2024b), the root mean square of successive differences (RMSSD), and the low frequency/high frequency (LF/HF) ratio (Wang and Huang, 2012) were determined as HRV parameters for each 5-min interval. The Baevsky SI represents autonomic SN activity (Huizinga et al.,

2025), whereas the LF/HF ratio depicts the ratio of SN and PN activity (Von Rosenberg et al., 2017). Therefore, an increase in these parameters indicates a higher physiological stress level. Conversely, the RMSSD is considered an indicator of parasympathetic activity (Baevsky and Chernikova, 2017) and is therefore inversely associated with stress levels. The HRV parameters for all 5-min intervals for a person were averaged before statistical evaluation of inquiry-based or communication activities.

Because HRV depends not only on mental stress (Thielmann and Boeckelmann, 2016), but also on movement intensity ([MI], Zetterman et al., 2023), we recorded it continuously at 1-s intervals using the 9-axis motion sensors of the Firstbeat system to be considered as a covariate. These tools are reliable for assessing external stress (Conte et al., 2025). Moreover, a questionnaire lasting approximately 10 min was administered to $n = 68$ students (64 of whom were assessable) immediately after the lesson. Because subjective stress perception often correlates only moderately with the physiological stress response (Minkley et al., 2021), we used the Visual Analog Scale (Lesage et al., 2012) in the questionnaire to assess perceived baseline stress levels in class (i.e., without linking them to specific situations). In addition, scientific SEB as a measure of available internal resources for managing stress (Thielmann and Böckelmann, 2021), was measured by adjusting the scale for school-related SEB (Jerusalem and Satow, 1999) (15 items, Cronbach's $\alpha = 0.852$, example item translated from German: "When I have to explain something using a complicated model in science class, I believe that I will be able to do so.").

Three linear mixed models (LMM; Hox et al., 2017) were calculated to investigate the dependence of physiological stress levels on teaching situations (rest period, inquiry-based activity, and communication). Each LMM had one of the above HRV parameters (SI, RMSSD, or LF/HF) as the dependent variable (fixed factors: Teaching situation and MI; random effects: Person ID; covariance type for repeated measurements: Compound symmetry covariance structure with a correlation metric; estimation: Restricted maximum likelihood). To assess any differences between the teaching situations, we calculated estimated marginal means (EMMs) and conducted pairwise comparisons with the Sidak correction (see, e.g., Hermann et al., 2020). We used partial eta-squared (η_p^2 , Richardson, 2011) to measure effect size. According to Cohen (1988), $\eta_p^2 = 0.01$ is considered a small effect, 0.06 a medium effect, and 0.14 a large effect.

Because stress reactions vary individually in other contexts (Negrão et al., 2000), we used a hierarchical cluster analysis to identify different patterns of personal dispositions, considering SEB, the perceived baseline stress, and the physiological baseline stress (SI) during the rest period (cluster method: Ward, distance measure: Squared euclidean distance). SI appeared to be the most appropriate physiological baseline, as it is derived from the frequency distribution of RR intervals (Huizinga et al., 2025) and was thus the most stable

parameter over time. We conducted a one-way analysis of variance (ANOVA) with Bonferroni-corrected *post hoc* tests to identify differences between the clusters in these dispositional variables. We calculated three additional LMMs to explore the dependence of SI, RMSSD, and LF/HF ratio on cluster membership in teaching situations, treating these clusters and the cluster-by-teaching-situation interaction as additional fixed factors.

FINDINGS

As Figure 1a-c indicate, no particularly relevant differences in SI, RMSSD, and LF/HF were observed between the inquiry-based activity and the non-inquiry-based (communication) situations. Even though the SI during the rest period barely differs from that in the other two teaching situations, evidence shows a decrease in RMSSD and an increase in the LF/HF ratio regarding the rest period. Thus, these parameters indicate higher physiological stress levels during inquiry-based activities and communication situations than during the rest period. As expected, the intensity of physical activity (MI) differs between teaching situations, with the highest level occurring during inquiry-based activities (Figure 1d).

As Table 1 presents, we used three LMMs to investigate whether these observations were statistically supported.

For RMSSD and LF/HF, significant main effects of teaching situations were found, with medium and large effect sizes, respectively (Cohen, 1988). No effect of MI was observed ($p > 0.05$). The SI model showed no significant effects. EMM revealed that both RMSSD and LF/HF indicated the lowest stress levels during the rest period, but similar levels of physiological stress during inquiry-based activity and communication. A pairwise comparison (Sidak-corrected) revealed significant differences only between the rest period and the two teaching situations, not between the two teaching situations themselves (Table 2). Therefore, we observed no general difference in stress levels between inquiry-based situations and communication situations.

We identified three clusters in the hierarchical cluster analysis described above based on obvious distance jumps in the

Table 1: Results of the linear mixed models (fixed effects: Teaching situation, MI; dependent variable: SI, RMSSD, or LF/HF)

HRV parameter	Effect	F (df1, df2)	p-value	η_p^2
SI	Teaching situation	0.10 (2, 120)	0.902	0.00
	MI	0.72 (1, 142)	0.398	0.01
RMSSD	Teaching situation	4.29 (2, 122)	≤0.050	0.07
	MI	1.45 (1, 148)	0.231	0.01
LF/HF	Teaching situation	11.33 (2, 128)	≤0.001	0.15
	MI	1.15 (1, 159)	0.284	0.01

HRV: Heart rate variability, SI: Stress index, MI: Movement intensity, RMSSD: Root mean square of successive differences, LF: Low frequency, HF: High frequency. Bold values indicate statistically significant differences

dendrogram. These clusters are referred to as Self-efficacious stressed (high SEB, high physiological and perceived baseline stress, $n = 15$), Unconscious burdened (low SEB, low perceived and high physiological baseline stress, $n = 14$),

and Self-efficacious relaxed (high SEB, low physiological and perceived baseline stress, $n = 35$, Figure 2). ANOVA reveals that the clusters differ significantly in all three dispositional variables (Table 3).

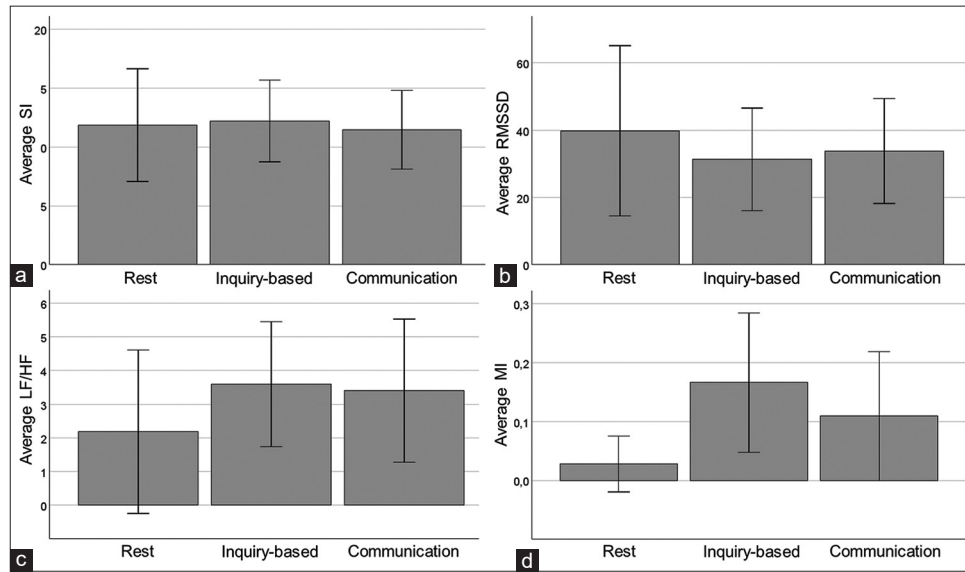


Figure 1: (a-d) Average stress index (a), root mean square of successive differences (b), low frequency/high frequency ratio (c), and movement intensity (d) during the three teaching situations (resting = rest period: $n = 86$, inquiry-based activity: $n = 47$, communication: $n = 62$)

Table 2: Estimated marginal means (EMM, only reported in case of significant main effects in Table 1) and pairwise comparisons

HRV parameter	Teaching situation	EMM (SE)	p-value		
			vs. Resting	vs. Inquiry-based	vs. Communication
RMSSD	Rest	38.96 (2.30)		0.066	≤ 0.050
	Inquiry-based	32.59 (2.75)	0.066		0.995
	Communication	33.13 (2.38)	≤ 0.050	0.995	
LF/HF	Rest	2.27 (0.25)		≤ 0.001	≤ 0.001
	Inquiry-based	3.53 (0.30)	≤ 0.001		0.876
	Communication	3.33 (0.26)	≤ 0.001	0.876	

HRV: Heart rate variability, EMM: Estimated marginal means, RMSSD: Root mean square of successive differences, LF: Low frequency, HF: High frequency, SE: Standard error. Bold values indicate statistically significant differences

Table 3: ANOVA including Bonferroni-corrected *post hoc* tests (reported only if significant)

Cluster variable	M (SD) A	M (SD) B	M (SD) C	F (df1, df2)	p-value	p-value <i>Post hoc</i>
Physiological baseline stress (SI rest)	14.25 (4.78)	16.29 (6.22)	9.54 (3.24)	14.09 (2, 61)	≤ 0.001	A>C ≤ 0.010 B>C ≤ 0.001
Perceived baseline stress	61.74 (10.23)	21.80 (15.88)	22.90 (15.78)	40.67 (2, 61)	≤ 0.001	A>B ≤ 0.001 A>C ≤ 0.001
SEB	1.71 (0.47)	1.04 (0.45)	1.95 (0.42)	21.59 (2, 61)	≤ 0.001	A>B ≤ 0.001 C>B ≤ 0.001

SEB: Self-efficacy beliefs, SI: Stress index, A: Self-efficacious stressed, B: Unconscious burdened, C: Self-efficacious relaxed, M: Mean, SD: Standard deviation, ANOVA: Analysis of variance

Figure 3a-c illustrates the three HRV parameters for each cluster in all teaching situations. Both the SI and the RMSSD indicate a greater increase in stress levels during inquiry-based situations only for the self-efficacious, relaxed students, with higher SI or lower RMSSD indicating higher physiological stress. The SI of the Self-efficacious stressed remains relatively constant, whereas the RMSSD of this cluster decreases slightly during both teaching situations compared with the rest period. Hence, the RMSSD indicates a moderately increased stress level during both teaching situations.

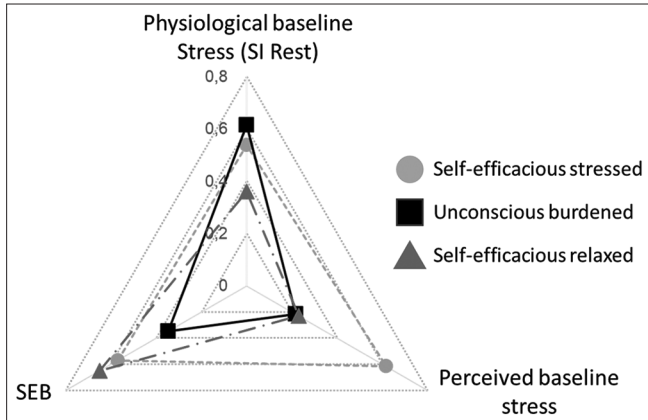


Figure 2: Dispositional characteristics of the three clusters, with each variable normalized to a maximum of 1 (SEB: Self-efficacy beliefs, SI: Stress index)

Nevertheless, the change in SI and RMSSD in the unconscious burdened cluster is particularly striking. Both HRV parameters indicate a moderate decrease in stress during class compared to the rest period, as discussed later. The LF/HF for all three clusters indicates a higher stress level during teaching situations than the rest period, somewhat deviating from the SI and RMSSD findings. The self-efficacious, stressed, and unconscious burdened clusters show slightly higher LF/HF in inquiry-based situations than in communication situations. Conversely, in the self-efficacious relaxed cluster, LF/HF is moderately higher in communication situations (Figure 3c).

To determine whether a dependency exists between physiological stress levels in class and individual dispositions, as suggested by SI and RMSSD, we recalculated the three LMMs mentioned above, including the cluster and the cluster $\times$ situation interaction as additional fixed effects (Table 4). Models that include SI or RMSSD as dependent variables reveal a significant main effect of cluster membership and the cluster $\times$ situation interaction on student stress (Table 4). The large effect sizes, especially those for the interactions, suggest the students' physiological stress responses strongly depend on their personal dispositions. Strikingly, the LF/HF-based model does not confirm this dependence. Rather, this model verifies that stress levels depend on the teaching situation.

As shown in Table 5, the main effect observed in the LMMs (Table 4) is due to the fact that the self-efficacious relaxed cluster differs significantly from the other two clusters.

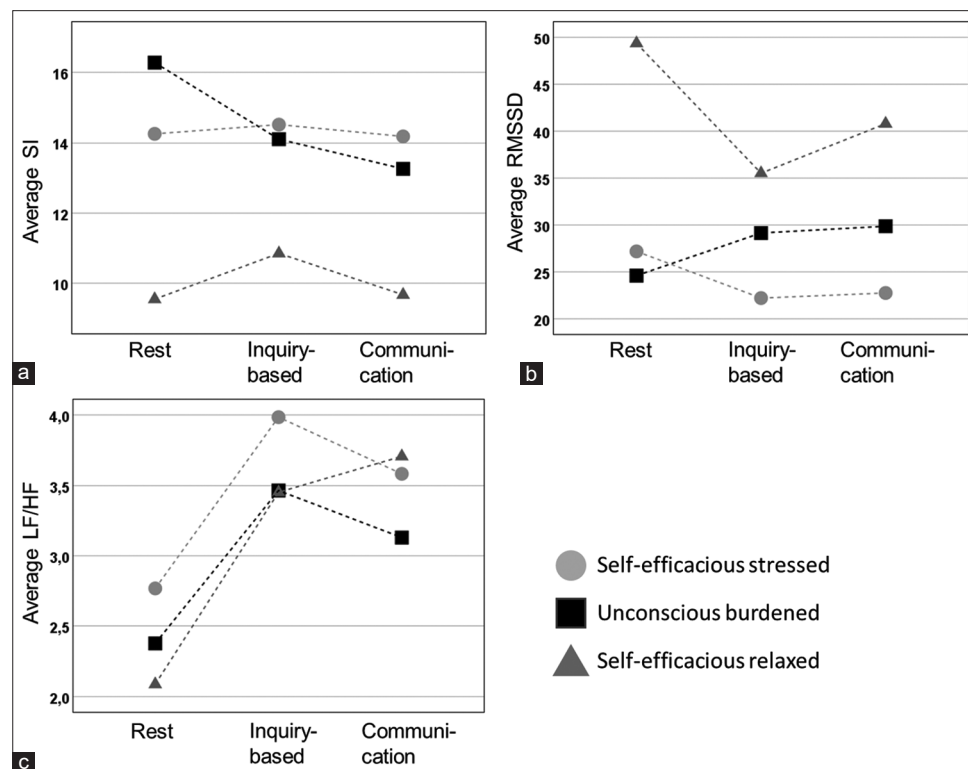


Figure 3: Stress index (a), root mean square of successive differences (b), and low frequency/high frequency (c) for each cluster in all teaching situations. Average values for each cluster are connected by dotted lines to underscore their differences

Therefore, both SI and RMSSD indicate that the physiological stress response depends on individual dispositions, whereas the LF/HF suggests that the teaching situation is significant for stress levels. Nonetheless, in the case of the LF/HF model, the main effect of the teaching situation is not explained by differences in stress between the inquiry-based and communication situations, but rather by stress levels during both teaching situations relative to the rest period (Table 6).

Table 4: Results of the recalculated LMM (additional fixed effects: cluster, cluster×teaching situation interaction)

HRV parameter	Effect	F (df1, df2)	p-value	η^2p
SI	Teaching situation	0.49 (2, 89)	0.614	0.01
	MI	0.04 (1, 108)	0.849	0.00
	Cluster	13.44 (2, 62)	≤0.001	0.30
	Cluster×Situation	4.73 (4, 84)	≤0.010	0.18
RMSSD	Teaching situation	1.62 (2, 90)	0.204	0.03
	MI	0.27 (1, 107)	0.608	0.00
	Cluster	7.48 (2, 63)	≤0.001	0.19
	Cluster×Situation	3.98 (4, 84)	≤0.010	0.16
LF/HF	Teaching situation	5.43 (2, 92)	≤0.050	0.11
	MI	1.27 (1, 113)	0.236	0.01
	Cluster	0.24 (2, 65)	0.788	0.01
	Cluster×Situation	0.19 (4, 86)	0.945	0.01

HRV: Heart rate variability, LMM: Linear mixed models, SI: Stress index, MI: Movement intensity, RMSSD: Root mean square of successive differences, LF: Low frequency, HF: High frequency. Bold values indicate statistically significant differences

Table 5: Estimated marginal means (EMM, only reported in the event of significant cluster main effects in Table 4) and pairwise comparisons

HRV parameter	Cluster	EMM (SE)	p-value		
			vs. A	vs. B	vs. C
SI	A	14.52 (0.89)		1.000	≤0.001
	B	14.64 (0.92)	1.000		≤0.001
	C	10.09 (0.58)	≤0.001	≤0.001	
RMSSD	A	23.61 (4.47)		0.939	≤0.010
	B	26.92 (4.59)	0.939		≤0.050
	C	41.81 (2.90)	≤0.010	≤0.050	

A: Self-efficacious stressed, B: Unconscious burdened, C: Self-efficacious relaxed, HRV: Heart rate variability, RMSSD: Root mean square of successive differences, SI: Stress index, EMM: Estimated marginal means, SE: Standard error. Bold values indicate statistically significant differences

Table 6: Estimated marginal means (EMM, only reported in the event of a significant teaching situation main effect in Table 4)

HRV parameter	Teaching situation	EMM (SE)	p-value		
			vs. Rest	vs. Inquiry-based	vs. Communication
LF/HF	Rest	2.52 (0.33)		≤0.050	≤0.050
	Inquiry-based	3.58 (0.39)	≤0.050		0.990
	Communication	3.47 (0.36)	≤0.050	0.990	

HRV: Heart rate variability, RMSSD: Root mean square of successive differences, SI: Stress index, EMM: Estimated marginal means, SE: Standard error. Bold values indicate statistically significant differences

DISCUSSION AND CONCLUSION

A comparison of the three HRV parameters across the teaching situations does not support the initial hypothesis that inquiry-based situations are inherently more stressful for students than non-inquiry-based situations. Even though RMSSD and the LF/HF ratio differ between situations, this effect indicates higher physiological stress during class than during the rest period. Because both classroom situations involved greater MI than the rest period, increased physiological stress might initially be associated with physical activity (Zetterman et al., 2023) rather than mental stress (Thielmann and Boeckelmann, 2016). To take account of the potential effect of MI, we included it as an additional fixed effect in the LMMs alongside teaching situation. Consequently, the estimated effects of teaching situation on HRV were adjusted for differences in MI. As MI did not significantly predict any of the HRV parameters, the observed differences are more plausibly linked to mental stress responses associated with the teaching situation.

The absence of expected differences across teaching situations may stem from the fact that the communication situations in the present study were derived from the communication skills defined in the German educational standards, which involve communicative activities with heterogeneous cognitive demands (KMK, 2024). As higher-level argumentative skills are moderately developed in comprehensive schools (Müller, 2025), limited resources in this area (Lazarus and Folkman, 1984) may result in elevated stress even in non-inquiry-based communication situations. Moreover, this exploratory field study encompassed various inquiry-based activities aligning with educational standards (KMK, 2024); future experimental studies should therefore refine the scope of teaching situations, particularly those with potentially high emotional stress, such as dissections (Kaiser et al., 2023). Another explanation is that students may have engaged in inquiry-related cognitive processes during seemingly non-inquiry-based communication situations. Nonetheless, one cannot capture such internal processes using an observation form like the one used in this study. Further studies could render these internal processes visible by using additional interviews (Roskam, 2020) or the thinking-aloud method (Schnell, 2016). However, the cognitive strain associated with these methods could adversely affect students' HRV (Hillmert et al., 2020). In addition, implementing these approaches would be challenging in a

field study but feasible in a laboratory setting. The absence of a significant teaching situation effect on SI in LMM could be attributable to the fact that, unlike RMSSD and LF/HF ratio, SI arises from the frequency distribution of RR intervals (Huizinga et al., 2025). Therefore, minor changes or differences in physiological stress may be reflected less evidently.

We identified three types of students in our study: The self-efficacious stressed, the unconscious burdened, and the self-efficacious relaxed. These students enter the teaching situation with markedly heterogeneous stress levels. Even though differences in stress levels across teaching situations facilitate conclusions about cluster-specific stress responses, the absolute levels of physiological stress across the three clusters should be interpreted cautiously. Numerous non-situational stressors, in addition to situational stressors, affect HRV (e.g., illness, lifestyle; Böckelmann and Sammito, 2020). Nevertheless, it is equally plausible that a rest period perceived heterogeneously across the clusters led to the differences in absolute physiological baseline stress levels. Other educational contexts suggest that students with low SEB are more likely to suffer from school anxiety (Qudsyi and Putri, 2016). Accordingly, one can assume that, due to their low SEB (Moeini et al., 2008), mere presence in the science classroom may be stressful for the unconscious burdened cluster, which could explain their high physiological baseline stress level. This situation would also account for the low physiological baseline stress of the self-efficacious relaxed group. As expected, based on these considerations, the SEB combined with physiological baseline stress (as shown by SI and RMSSD) exists between the other two clusters for the self-efficacious stressed in the rest period. Nonetheless, the inclusion of physiological parameters in the study could have caused iatrophobia in students (fear of doctors or medical examinations; Hollander and Greene, 2019), leading to the impression of a medical examination and, in turn, to high baseline physiological stress, regardless of their SEB (Fabian et al., 2025). Nevertheless, because estimates suggest that iatrophobia impacts only around 2.4% of the German population (dpa/tmn, 2018), this potential effect is negligible.

Nonetheless, the heterogeneous changes in SI and RMSSD across the three clusters in inquiry-based and non-inquiry-based communication situations during the rest period (evidenced by the significant cluster $\times$ situation interaction) are more important than the absolute level of physiological stress. For the cluster with the lowest SEB in science (unconscious burdened), one would expect teaching to be particularly stressful due to limited resources (Lazarus and Folkman, 1984; Moeini et al., 2008). Interestingly, the stress level during class is lower compared to the rest period for this cluster. Conversely, the other two clusters (with higher SEB) demonstrate a slightly increased or constant stress level during class. A possible explanation stems from the distinction between distress and eustress. Distress (negative stress) is considered burdensome, and can cause anxiety or feelings of helplessness. Conversely, eustress (positive stress) situations are perceived as a challenge (Ernst et al., 2022). Eustress urges people to actively tackle

this challenge (Reif & Spieß, 2018a; Patwary et al., 2025). People with high SEB are more likely to experience eustress and navigate distress better than those with low SEB (Galindo-Domínguez and Bezanilla, 2021). Moreover, SEB is a key predictor of motivation, engagement, and active class participation (Nong et al., 2023; Basileo et al., 2024). Given this fact, one can assume that the unconscious burdened cluster, due to its low scientific SEB, is less actively involved in inquiry-based activities and communication and adopts a more distant attitude. A common coping or avoidance strategy for stress involves taking psychological distance (Schuitema and Lacchia, 2025). Even though this approach does not address the cause of stress, this type of coping can also temporarily reduce the stress response (e.g., during the lesson) (Reif & Spieß, 2018b). Therefore, the physiological stress experienced by the unconscious burdened in class is lower than during the resting phase. This finding aligns with their relatively low perceived baseline stress reported in the questionnaire. Nonetheless, emotional distance from the classroom is an unfavorable learning condition (Chen et al., in press). Similarly, due to their relatively high SEB, one can assume that the self-efficacious relaxed and the self-efficacious stressed perceive challenges and eustress in communication and inquiry-based activities. As indicated by the SI and RMSSD, this circumstance is slightly more pronounced in the self-efficacious relaxed group during inquiry-based activities than in communication situations. Nevertheless, the differences between communication and inquiry-based activities at the cluster level are also marginal, suggesting that the observed cluster $\times$ situation interaction (in SI and RMSSD) is more likely driven by differences in changes in physiological stress regarding the resting phase. Unlike the other two HRV parameters, no significant interaction between cluster $\times$ situation was observed for the LF/HF ratio. This observation may simply reflect the strong dependence of the LF/HF ratio on the respiratory cycle (Shaffer and Ginsberg, 2017). Accordingly, its findings alone should not be overinterpreted (Brisinda et al., 2024a). However, future laboratory studies should explore the replicability of the HRV-based clusters and their stress reactions. These studies should consider additional physiological stress markers, such as saliva cortisol in (Matousek et al., 2010) and electrodermal activity (Boucsein, 1988). This field study did not address this issue; rather, it favored ensuring lessons ran smoothly and achieving potentially higher ecological validity (van Doornen and Turner, 1992). Furthermore, the relative sizes and composition of the identified clusters (self-efficacious stressed: $n = 15$, unconscious burdened: $n = 14$, self-efficacious relaxed: $n = 35$) reflect the present sample and should not be interpreted as representative of the broader student population. Therefore, the identified clusters should be considered exploratory patterns that require validation in additional samples.

In closing, the present exploratory field study provides no conclusive evidence that inquiry-based activities in science classes typically cause markedly high physiological stress. Rather, the identified clusters indicated the inter-individual

variability of stress. In line with the transactional stress model (Lazarus and Folkman, 1984), our study demonstrates that scientific SEB is a relevant factor in determining physiological stress levels. Hence, our results provide a foundation for future studies on stress prevention in science education. Moreover, they can raise awareness among (prospective) science teachers about their (future) students' individual stress responses. In particular, the identified clusters illustrate that students may respond differently to the same science teaching situation, with some students showing increased physiological stress responses during learning activities, whereas others show stable or reduced responses. Developing such awareness is particularly relevant because teachers often find it difficult to assess students' affective characteristics (Zurbriggen et al., 2023). Furthermore, understanding students' individual needs provides the basis for designing science learning environments that adequately address students' diverse needs (Whiting et al., 2021). Providing appropriate scaffolding and supportive learning conditions may not only support students' cognitive engagement (van Nooijen et al., 2024) with challenging science activities but also help them perceive such demands as manageable rather than overwhelming burdens.

ETHICS STATEMENT

The Ethics Committee of the Europa-Universität Flensburg provided the ethical approval for our study. We informed parents or guardians of the students in writing that data would be anonymized and could be used for publication.

PERMITS FOR ACCESS & FUNDING SOURCE

The Ministerium für Allgemeine und Berufliche Bildung, Wissenschaft, Forschung und Kultur des Landes Schleswig-Holstein (Ministry for General and Vocational Education, Science, Research and Culture of Schleswig-Holstein) granted permission to conduct the study, and the study was funded through the ministry's open-topic funding program.

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REFERENCES

- Badura, P., García-Moya, I., Wilson, M., Inchley, J., Eriksson, C., Löfstedt, P., Melkumova, M., Sotiroska, K., & Brown, J. (2024). *A Focus on Adolescent Social Contexts in Europe, central Asia and Canada: Health Behaviour in School-aged Children International Report from the 2021/2022 Survey*. Vol. 7. World Health Organization. Available from: <https://eprints.gla.ac.uk/343269> [Last accessed on 2026 Sep 01]
- Baevsky, R.M., & Chernikova, A.G. (2017). Heart rate variability analysis: Physiological foundations and main methods. *Cardiometry*, 10, 66-76.
- Bandura, A. (2002). Social foundations of thought and action. In D. F. Marks (Ed.), *The Health Psychology Reader* (pp. 94-106). SAGE. <https://doi.org/10.4135/9781446221129.n6>
- Basileo, L.D., Otto, B., Lyons, M., Vannini, N., & Toth, M.D. (2024). The role of self-efficacy, motivation, and perceived support of students' basic psychological needs in academic achievement. *Frontiers in Education*, 9, 1385442.
- Bäuerle, S., & Kury, H. (1980). Stress in der Schule. Eine experimentelle Untersuchung an 13-bis 16jährigen Schülern [Stress at school. An experimental study of 13- to 16-year-old students]. *Praxis Der Kinderpsychologie Und Kinderpsychiatrie*, 29(2), 70-76.
- Böckelmann, I., & Sammito, S. (2020). Herzfrequenzvariabilitätsanalyse in der betriebsärztlichen praxis [heart rate variability analysis in occupational health practice]. *Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie*, 70(6), 269-277.
- Boucein, W. (1988). *Elektrodermale Aktivität: Grundlagen, Methoden und Anwendungen* [Electrodermal Activity: Fundamentals, methods, and Applications]. Germany: Springer-Verlag, Springer Berlin Heidelberg.
- Bozovic, D., Racic, M., & Ivkovic, N. (2013). Salivary cortisol levels as a biological marker of stress reaction. *Medical Archives*, 67(5), 374-377.
- Brisinda, D., Picerni, M., Fenici, P., & Fenici, R. (2024a). Rapid assessment of cardiac autonomic modulation and adaptive stress responses: Automatic calculation of time-varying parasympathetic, sympathetic, and Baevsky stress indexes. *Brain and Heart*, 2(4), 3503.
- Brisinda, D., Picerni, M., Fenici, P., & Fenici, R. (2024b). Synthetic assessment of cardiac autonomic modulation and Baevsky stress index in patients with synucleinopathies. *European Heart Journal*, 45(Suppl 1), ehae666.3017.
- Camm, A.J., Malik, M., Bigger, J.T., Breithardt, G., Cerutti, S., Cohen, R.J., Coumel, P., Fallen, E.L., Kennedy, H.L., Kleiger, R.E., Lombardi, F., Malliani, A., Moss, A.J., Rottman, J.N., Schmidt, G., Schwartz, P.J., & Singer, D.H. (1996). Heart rate variability: Standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of pacing and electrophysiology. *Circulation*, 93(5), 1043-1065.
- Chen, G., Han, G., Niu, J., & He, J. Understanding the impact of emotional engagement on learning outcomes in online education: An automated analysis approach. *Scientific Reports*.
- Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Mahwah: Erlbaum.
- Conte, D., Rampinini, E., Trimarchi, F., & Ferioli, D. (2025). Interunit reliability of firstbeat sport sensors as accelerometer-based tracking devices in basketball. *International Journal of Sports Physiology and Performance*, 20(5), 727-730.
- Copeland, E.P., & Hess, R.S. (1995). Differences in young adolescents' coping strategies based on gender and ethnicity. *The Journal of Early Adolescence*, 15(2), 203-219.
- dpa/tmn. (2018). Tipps für Patienten mit Angst vor dem Arzt [Tips for Patients with Fear of the Doctor]. *Süddeutsche Zeitung*. Available from: <https://www.sueddeutsche.de/gesundheit/gesundheits-tipps-fuer-patienten-mit-angst-vor-dem-arzt-dpa.urn-newsml-dpa-com-20090101-180612-99-690161> [Last accessed on 2026 Sep 01].
- Ernst, G., Franke, A., & Franzkowiak, P. (2022). Stress und Stressbewältigung [Stress and Stress Management]. In: BZgA. (Ed.), *Leitbegriffe der Gesundheitsförderung und Prävention: Glossar zu Konzepten, Strategien und Methoden*.
- Eronen, T., Lipponen, J.A., Hyrylä, V.V., Kupari, S., Mursu, J., Venojärvi, M., Tikkanen, H. O., & Tarvainen, M.P. (2024). Heart Rate Variability Based Ventilatory Threshold Estimation - Validation of a Commercially Available Algorithm. *MedRxiv* [PrePrint].
- Fabian, R.A., Lourdes, M.A., & Francisco, G.R. (2025). Exploring virtual reality-induced anxiety in iatrophobia: A pilot study for future exposure therapy. *Ieee Access*, 13, 130570-130584.
- Galindo-Domínguez, H., & Bezanilla, M.J. (2021). The importance of personality and self-efficacy for stress management in higher education. *International Journal of Educational Psychology*, 10(3), 247-270.
- Grasaas, E., Ostojic, S., Sandbakk, Ø., Bjørnsen, G., Sylta, Ø., Høgli Major, D., & Jahre, H. (2024). The relationship between perceived school stress and satisfaction with life among Norwegian school-based adolescents and the moderating role of perceived teacher care: A cross-sectional study. *BMC Public Health*, 24(1), 2771.
- Hansen, J., Neumann, C., & Hanewinkel, R. (2023). *Präventionsradar: Wohlbefinden und Gesundheitsverhalten von Kindern und Jugendlichen in Deutschland - Ausgewählte Ergebnisse des Präventionsradars 2022/23* [Prevention radar: Well-being and health behaviors of children

- and adolescents in Germany - Selected results from the prevention radar 2022/23]. IFT-Nord. Available from: <https://caas.content.dak.de/caas/v1/media/40840/data/a9018013330bc9ade945734aeb266476/praeventionsradar-ergebnisbericht-2022-2023.pdf> [Last accessed on 2026 Sep 01].
- Hermann, G.M., Iovoli, A.J., Platak, A.J., Wang, C., Miller, A., Attwood, K., Bourgeois, D.J., & Singh, A.K. (2020). A single-institution, randomized, pilot study evaluating the efficacy of gabapentin and methadone for patients undergoing chemoradiation for head and neck squamous cell cancer. *Cancer*, 126(7), 1480-1491. <https://doi.org/10.1002/cncr.32676>
- Hess, R.S., & Copeland, E.P. (2001). Students' stress, coping strategies, and school completion: A longitudinal perspective. *School Psychology Quarterly*, 16(4), 389-405.
- Hillmert, M., Bergmüller, A., Minow, A., Raggatz, J., & Böckelmann, I.I. (2020). Psychophysiologische Beanspruchungskorrelate während kognitiver Belastung [Psychophysiological strain correlates during cognitive load]. *Zentralblatt für Arbeitsmedizin, Arbeitsschutz und Ergonomie*, 70(4), 149-163.
- Hoferichter, F., & Raufelder, D. (2022). Kann erlebte Unterstützung durch Lehrkräfte schulische Erschöpfung und Stress bei Schülerinnen und Schülern abfedern? [Can perceived support from teachers buffer academic exhaustion and stress in students?]. *Zeitschrift für Pädagogische Psychologie*, 36(1-2), 101-114.
- Hoferichter, F., Jentsch, A., Maas, L., & Hagemann, G. (2023). Burnout among high school students is linked to their telomere length and relatedness with peers. *The International Journal on the Biology of Stress*, 26(1), 2240909.
- Hollander, M.A.G., & Greene, M.G. (2019). A conceptual framework for understanding iatrophobia. *Patient Education and Counseling*, 102(11), 2091-2096.
- Hox, J., Moerbeek, M., & Van de Schoot, R. (2017). *Multilevel Analysis: Techniques and Applications*. United Kingdom: Routledge.
- Huizinga, J.D., Chen, J.H., Hussain, A., Zheng, D., Liu, L., Lui, H., Pan, M., Chen, X., DiBattista, B., Alam, M., & Niro, J. (2025). Determining autonomic sympathetic tone and reactivity using Baevsky's stress index. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, 328(5), R562-R577.
- Jerusalem, M., & Satow, L. (1999). Schulbezogene Selbstwirksamkeitserwartung [School-related self-efficacy beliefs]. In: Schwarzer, R., & Jerusalem, M., (Eds.), *Skalen zur Erfassung von Lehrer- und Schülermerkmalen*. Freie Universität Berlin, pp. 15-16.
- Jin, N., Tian, J., Li, Y., & Mi, J. (2022). A validation study of heart rate variability index in monitoring basketball training load. *Frontiers in Physiology*, 13, 881927.
- Kaiser, L.M., Polte, S., Kirchhoff, T., Großmann, N., & Wilde, M. (2023). Dissection in biology education compared to alternative methods in terms of their influence on students' emotional experience. *Frontiers in Psychology*, 14, 1138273.
- Kim, H.G., Cheon, E.J., Bai, D.S., Lee, Y.H., & Koo, B.H. (2018). Stress and heart rate variability: A meta-analysis and review of the literature. *Psychiatry Investigation*, 15(3), 235-245.
- Kim, H.J., Park, Y., & Lee, J. (2024). The validity of heart rate variability (HRV) in educational research and a synthesis of recommendations. *Educational Psychology Review*, 36(2), 42.
- KMK. (2024). *Weiterentwickelte Bildungsstandards in den Naturwissenschaften für das Fach Biologie (MSA)*. Beschluss der Kultusministerkonferenz vom 16.12.2004 i.d.F. vom 13.06.2024 [Advanced Educational Standards in the Sciences for the Subject of biology (MSA)]. Available from: https://www.kmk.org/fileadmin/Dateien/veroeffentlichungen_beschluesse/2024/2024_06_13-WeBiS_Biologie_MSA.pdf [Last accessed on 2026 Sep 01].
- Knittel, T., Schneidenbach, T., & Mohr, S. (2015). *Juvenir-Studie 4.0 Zuviel Stress – zuviel Druck! Wie Schweizer Jugendliche mit Stress und Leistungsdruck Umgehen* [Juvenir study 4.0: Too Much Stress—too Much Pressure! How Swiss Adolescents cope with Stress and Performance Pressure]. Jacobs Foundation. Available from: https://jacobsfoundation.org/wp-content/uploads/2017/07/juvenir-4.0_langfassung_de_final.pdf
- Krammer, U.D.B., Lerch, M.L., Haslberger, A.G., & Hippe, B. (2023). Mir-10a, miR-15a, let-7a, and let-7g expression as stress-relevant biomarkers to assess acute or chronic psychological stress and mental health in human capillary blood. *Molecular Biology Reports*, 50(7), 5647-5654.
- Lazarus, R.S., & Folkman, S. (1984). *Stress, Appraisal, and Coping*. Berlin: Springer.
- Lesage, F.X., Berjot, S., & Deschamps, F. (2012). Clinical stress assessment using a visual analogue scale. *Occupational Medicine*, 62(8), 600-605.
- Lewalter, D., Diedrich, J., Goldhammer, F., Köller, O., & Reiss, K. (2023). *PISA 2022: Analyse der Bildungsergebnisse in Deutschland* [PISA 2022: Analysis of Educational Outcomes in Germany]. Germany: Waxmann Verlag.
- Martínez-Libano, J., & Yeomans-Cabrera, M.-M. (2024). Depression, anxiety, and stress in the Chilean Educational System: Children and adolescents post-pandemic prevalence and variables. *Frontiers in Education*, 9, 1407021.
- Matousek, R.H., Dobkin, P.L., & Pruessner, J. (2010). Cortisol as a marker for improvement in mindfulness-based stress reduction. *Complementary Therapies in Clinical Practice*, 16(1), 13-19.
- Minkley, N., Kärner, T., Jojart, A., Nobbe, L., & Krell, M. (2018). Students' mental load, stress, and performance when working with symbolic or symbolic-textual molecular representations. *Journal of Research in Science Teaching*, 55(8), 1162-1187.
- Minkley, N., Lucas, M., & Bernholt, S. (2024). Effects of (short) clues on performance, stress, and self-efficacy in the accomplishment of tasks with complex molecular representations. *Research in Science Education*, 54(6), 1117-1135.
- Minkley, N., Ringeisen, T., Josek, L.B., & Kärner, T. (2017). Stress and emotions during experiments in biology classes: Does the work setting matter? *Contemporary Educational Psychology*, 49, 238-249.
- Minkley, N., Xu, K.M., Krell, M., & Xu, K.M. (2021). Analyzing relationships between causal and assessment factors of cognitive load: Associations between objective and subjective measures of cognitive load, stress, interest, and self-concept. *Frontiers in Education*, 6, 632907.
- Moeini, B., Shafii, F., Hidarnia, A., Babaii, G.R., Birashk, B., & Allahverdipour, H. (2008). Perceived stress, self-efficacy and its relations to psychological well-being status in Iranian male high school students. *Social Behavior and Personality: An International Journal*, 36(2), 257-266.
- Müller, H.G. (2025). Zur Entwicklung schriftlicher argumentativer Kompetenzen in der Sekundarstufe [On the development of written argumentative skills in secondary education]. *Didaktik Deutsch*, 30(58), 55-74.
- Negrão, A.B., Deuster, P.A., Gold, P.W., Singh, A., & Chrousos, G.P. (2000). Individual reactivity and physiology of the stress response. *Biomedicine and Pharmacotherapy*, 54(3), 122-128.
- Nong, W., Ye, J.H., Chen, P., & Lee, Y.S. (2022). A study on the blended learning effects on students majoring in preschool education in the post-pandemic era: An example of a research-method course in a Chinese university. *Frontiers in Psychology*, 13, 962707.
- Núñez-Regueiro, F., & Núñez-Regueiro, S. (2021). Identifying salient stressors of adolescence: A systematic review and content analysis. *Journal of Youth and Adolescence*, 50(12), 2533-2556.
- OECD. (2017). *PISA 2015—Results (Volume III): Students' Well-Being*. Paris: OECD Publishing.
- Patwary, M.M., John, A., Park, S., Zhao, Y., Kwak, D.H., & Patuwo, B. (2025). Can gamification change learners' ability and motivation? Role of eustress in the context of gamified ERP training. *Journal of Information Systems Education*, 35(2), 148-165.
- Qudsyi, H., & Putri, M.I. (2016). Self-efficacy and anxiety of national examination among high school students. *Procedia - Social and Behavioral Sciences*, 217, 268-275.
- Reif, J., Spieß, E., & Stadler, P. (Eds.). (2018). *Effektiver Umgang mit Stress: Gesundheitsmanagement im Beruf* [Effective coping with stress]. Berlin Heidelberg: Springer.
- Reif, J.A., & Spieß, E. (2018b). Wahrnehmung und Bewertung von Stressoren [Perception and evaluation of stressors]. In: Reif, J., Spieß, E., & Stadler, P. (Eds.), *Effektiver Umgang mit Stress: Gesundheitsmanagement im Beruf*. Berlin Heidelberg: Springer, pp. 43-52.
- Reif, J.A.M., & Spieß, E. (2018a). Psychologische Modelle zu Anforderungen und Ressourcen [Psychological models of demands and resources]. In: Reif, J., Spieß, E., & Stadler, P. (Eds.), *Effektiver*

- Umgang mit Stress: Gesundheitsmanagement im Beruf*. Springer Berlin Heidelberg, pp. 75-81.
- Reiß, F., Napp, A.-K., Erhart, M., Devine, J., Dadaczynski, K., Kaman, A., & Ravens-Sieberer, U. (2023). Perspektive Prävention: Psychische Gesundheit von Schülerinnen und Schülern in Deutschland [Prevention perspective: mental health of schoolchildren in Germany]. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz*, 66(4), 391-401.
- Richardson, J.T. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review*, 6(2), 135-147.
- Robert Bosch Stiftung. (2024). *Deutsches Schulbarometer: Befragung Schüler: Innen: Ergebnisse von 8- bis 17-Jährigen und ihren Erziehungsberechtigten zu Wohlbefinden, Unterrichtsqualität und Hilfesuchverhalten* [German School Barometer: Student survey—Findings from 8- to 17-year-olds and their parents on well-being, teaching quality, and help-seeking behavior]. Available from: https://www.bosch-stiftung.de/sites/default/files/publications/pdf/2024-11/deutsches%20schulbarometer_sch%3bc3%bccler_2024.pdf
- Roskam, A. (2020). *Kognitive Verarbeitungsprozesse in der Interaktion mit Strömungsexperimenten in einer Ausstellung* [Cognitive Processing in Interaction with Flow Experiments in an Exhibition]. Germany: Springer Fachmedien Wiesbaden.
- Sammito, S., Darius, S., & Böckelmann, I. (2011). Validierungsstudie zum Einsatz eines funktionslosen Brustgurtsystems zur Messung der Herzratenvariabilität unter Ruhebedingungen und in Fahrzeugen [Validation study for the use of a non-transmitting memory belt for recording heart rate variability under resting conditions and inside vehicles]. *Arbeitsmed Sozialmed Umweltmed*, 46(2), 60.
- Satow, L., & Bäßler, J. (1998). Selbstwirksamkeit und körperliches Befinden Jugendlicher [Self-efficacy and physical well-being of adolescents]. *Unterrichtswissenschaft*, 26(2), 127-139.
- Schmitz, J., Wolf, K., & Bauch, J. (2024). Stichwort: Prävention psychischer Störungen von Schüler: Innen in Schule und Unterricht [Keyword: Prevention of mental disorders in students at school and in teaching]. *Psychologie in Erziehung Und Unterricht*, 71(2), 96-100.
- Schnell, C. (2016). Lautes Denken“ als qualitative Methode zur Untersuchung der Validität von Testitems [“Think aloud” as a qualitative method for examining the validity of test items]. *Zeitschrift für ökonomische Bildung*, (5), 26-49.
- Schuitema, G., & Lacchia, A. (2025). From anxiety to coping: Understanding psychological distance and coping skills for climate change and COVID-19 in 10-12-year-old children. *PLoS One*, 20(2), e0317725.
- Seiffge-Krenke, I. (2008). Schulstress in Deutschland: Ursachen, Häufigkeiten und internationale Verortung [Stress in German schools: Frequencies, causes and international comparison]. *Praxis der Kinderpsychologie und Kinderpsychiatrie*, 57(1), 3-19.
- Seiffge-Krenke, I. (2021). School-related stressors in adolescents from 21 countries: What is universal? *Internal Medicine Review*, 7(1), 1-18.
- Shaffer, F., & Ginsberg, J.P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5, 258.
- Stanat, P., Schipolowski, S., Mahler, N., Weirich, S., & Henschel, S. (2019). *IQB-Bildungstrend 2018. Mathematische und Naturwissenschaftliche Kompetenzen am Ende der Sekundarstufe I im Zweiten Ländervergleich* [IQB Bildungstrend 2018: Mathematical and Scientific Competencies at the End of Lower Secondary Education in the Second Cross-State Comparison]. Münster: Waxmann.
- Stone, A. A., & Shiffman, S. (2002). Capturing Momentary, Self-Report Data: A Proposal for Reporting Guidelines. *Annals B Behavioral Medicine*, 24(3), 236-243.
- Tarvainen, M.P., Niskanen, J.P., Lipponen, J. A., Ranta-Aho, P.O., & Karjalainen, P.A. (2014). Kubios HRV—Heart rate variability analysis software. *Computer Methods and Programs in Biomedicine*, 113(1), 210-220.
- Tarvainen, M.P., Ranta-Aho, P.O., & Karjalainen, P. A. (2002). An advanced detrending method with application to HRV analysis. *Ieee Transactions on Biomedical Engineering*, 49(2), 172-175.
- Thielmann, B., & Böckelmann, I. (2021). Die rolle von persönlichen ressourcen bei der stressbewältigung [the role of personal resources in coping]. *PPmP - Psychotherapie Psychosomatik Medizinische Psychologie*, 71(3-4), 107-115.
- Thielmann, B., & Boeckelmann, I. (2016). Herzfrequenzvariabilität als Beanspruchungsindikator für psychische Belastungen bei Chirurgen - ein Literaturüberblick [Heart rate variability as an indicator of mental stress in surgeons—a review of the literature]. *Zentralblatt für Chirurgie - Zeitschrift für Allgemeine, Viszeral-, Thorax- und Gefäßchirurgie*, 141(5), 577-582.
- TK. (2021). *Stressstudie „Entspann dich, Deutschland!“: TK-Stressstudie 2021* [Stressstudy“Relax,Germany!”:TK StressStudy2021]. Available from: <https://www.tk.de/resource/blob/2033600/dabd321631964c329be93cf716020397/entspann-dich-deutschland-data.pdf>
- Van Doornen, L.J.P., & Turner, J.R. (1992). The ecological validity of laboratory stress testing. In: Turner, J.R., Sherwood, A., & Light, K.C. (Eds.), *Individual Differences in Cardiovascular Response to Stress*. Boston, MA: Springer, pp. 63-83.
- Van Nooijen, C.C.A., Koning, B.B.D., Bramer, W.M., Isahakyan, A., Asoodar, M., Kok, E., van Merriënboer, J.J.G., & Paas, F. (2024). A cognitive load theory approach to understanding expert scaffolding of visual problem-solving tasks: A scoping review. *Educational Psychology Review*, 36(1), 12.
- Von Rosenberg, W., Chanwimalueang, T., Adjei, T., Jaffer, U., Goverdovsky, V., & Mandic, D.P. (2017). Resolving ambiguities in the LF/HF Ratio: Lf-HF scatter plots for the categorization of mental and physical stress from HRV. *Frontiers in Physiology*, 8, 360.
- Wang, H.M., & Huang, S.C. (2012). Sdnn/rmssd as a surrogate for LF/HF: A revised investigation. *Modelling and Simulation in Engineering*, 2012(1), 1-8.
- Webersen, Y., & Riese, J. (2025). Umdenken! Vom fachlichen zum schulischen Experimentieren [Rethinking! from academic to school-based experimentation]. *Herausforderung Lehrer*Innenbildung - Zeitschrift zur Konzeption, Gestaltung und Diskussion (HLZ)*, 8(1), 99-121.
- Wehrle, M. (2011). *Handbuch Fantasiereisen: Für Training, Coaching, Beratung, Jugendarbeit und Therapie* [Handbook of Guided Imagery: For Training, Coaching, Counseling, Youth Work, and Therapy]. New York: Katheren Caldwell.
- Wendland, A., & Jansen, L. J. (2018). Dispositionelle Stressreaktivität, Ressourcen und chronischer Stress im Dienstleistungsbereich [Dispositional stress reactivity, resources, and chronic stress in the service sector]. In: Fernhochschule, S.R.H. (Ed.), *Demografischer Wandel: Aufbruch in Eine Altersgerechte Arbeitswelt*. Springer, pp. 69-85.
- Whiting, S.B., Wass, S.V., Green, S., & Thomas, M.S.C. (2021). Stress and learning in pupils: Neuroscience evidence and its relevance for teachers. *Mind, Brain and Education*, 15(2), 177-188.
- Willis, A., Grainger, P., Menzies, S., Dwyer, R., Simon, S., & Thiele, C. (2021). The role of teachers in mitigating student stress to progress learning. *Australian Journal of Education*, 65(2), 122-138.
- Zetterman, T., Markkula, R., Miettinen, T., & Kalso, E. (2023). Heart rate variability responses to cognitive stress in fibromyalgia are characterised by inadequate autonomous system stress responses: A clinical trial. *Scientific Reports*, 13(1), 700.
- Zurbriggen, C.L., Nusser, L., Krischler, M., & Schmitt, M. (2023). Teachers' judgment accuracy of students' subjective well-being in school: In search of explanatory factors. *Teaching and Teacher Education*, 133, 104304.