communicated by:
Lehr- und Forschungsgebiet Informatik 9

Prof Dr. Ulrik Schroeder

The present work was submitted to the Learning Technologies Research Group
Diese Arbeit wurde vorgelegt am Lehr- und Forschungsgebiet Lerntechnologien

Heart Rate in Multimodal Learning Analytics in Educational Virtual Reality

Master-Thesis
Masterarbeit

presented by / von

Huang, Pu
414498

Examined by / Begutachtet von

Prof. Ulrik Schroeder

Prof. Torsten Kuhlen

Supervised by / Betreut von

Birte Heinemann, Jasmin Hartanto

Aachen, September 21, 2025

Contents

List of Figures

List of Tables

List of Listings

Abstract

Virtual Reality (VR) is revolutionizing teacher education by offering immersive training environments where developers can provide teacher trainees with diverse classroom simulations. As one of the most challenging aspects of teaching, managing students' behavior often leads to high stress levels among educators. Mental stress has been shown to affect heart rate. This study aims to present heart rate monitoring in VR-based teacher training application Teach-R by collecting and visualizing heart rate data. To achieve this, the Polar H10 hearing rate sensor and learning analytics tools such as OmiLAXR and xAPI are used to track and record the heart rate of users. Real-time visualization in Teach-R and post-session visualization in CoachVR are presented to help users understand and assess their own performance during the session. In the user study, both visualizations are perceived as a practical tool to provide information on heart rate and student behavior. However, the presence of real-time visualization in Teach-R and the clarity of post-session visualization in Teach-R still leave room for improvement. Alternative real-time visualizations and possible clearer guidance for post-session visualizations are proposed to better support user reflection and teaching improvement.

Chapter 1 Introduction

Many people may experience a sudden acceleration of their heartbeat. A racing heart is also quite common among new teachers. The classroom is a high-stakes social arena. Teachers often face anticipatory stress before lessons even begin. This correlates directly with poorer teaching quality and reduced student engagement. Teachers who are stressed tend to struggle to deliver effective lessons.

1.1 Classroom Management

The concept of classroom management

The concept of classroom management is broader in scope than that implied in more old-fashioned terms like discipline or control (cf. [Mar90]). The term denotes more than these words. According to [Doy86], the first goal of classroom management is to create a quiet and calm learning environment that enables students to engage in meaningful subject learning. The second goal is to support students' social and moral development, fostering both their academic and social growth. We can conclude classroom management as the actions teachers take to create an environment that supports and facilitates both academic and social-emotional learning (cf. [EW06]). Educators consistently emphasize the importance of classroom management as a fundamental pedagogical skill that teachers must master to maximize classroom instruction (cf. [ES01]).

Classroom management can lead to stress

Classroom management is a stress-inducing aspect of teaching. Student misbehavior is one of the most cited causes of teacher stress (cf. [LGRM08]).

Poorly managed classrooms are usually characterized by disruptive behaviors such as sleeping, tardiness, noise-making, incorrect note-taking, eating, name-calling, and verbal or physical threats to fellow students or the teacher (cf. [Eke06]).

Novice teachers are facing great challenges

Novice teachers often face challenges in maintaining discipline, handling disruptions, and managing student interactions while simultaneously delivering instruction (cf. [SF18]). The perception some teachers have that they are unable to live up to the ideals that led them to the teaching profession in the first place often leads them to quit (cf. [Pos13]). Novice teachers are particularly vulnerable, with 40–50% leaving within the first five years, often citing classroom discipline issues as a primary reason (cf. [Ing01]). In secondary school, the perceived classroom management self-efficacy of teachers is often low. Around half of secondary school teachers across OECD member countries reported that their training did not include this competence (cf. [OEC20]).

Although effective classroom management practices have been identified, a significant gap exists between the effective classroom management research base and teacher training (cf. [FSBMG13]). According to [OR10], 27% of sampled special educator preparation programs contained a specific classroom management course (n = 26 programs), and 4% of sampled physical educator preparation programs (n = 134 programs (cf. [LFH12]). Generally, traditional teacher training programs lack classroom complexity, new teachers are often unprepared for real-word classroom management. To address this issue, Virtual Reality (VR) has emerged as an innovative tool for teacher training, allowing teacher trainers to simulate classroom experiences, practice management strategies, and receive structured feedback in a controlled environment (cf. [WMS22]).

1.2 Teacher Training in VR

Teacher training in VR is safe and positive

VR teacher training offers risk-free, immersive learning environments with immediate and detailed feedback on verbal and non-verbal interactions (cf. [AMRH^{+}24]). According to [GG20], traditional classroom placements are high-pressure environments, leaving little room for experimentation. Additionally, mistakes in traditional classrooms can lead to loss of classroom control, credibility issues with mentor teachers, or missed learning opportunities. In contrast, teacher training in VR can create a safe space for trial and error, providing feedback without severe real-world consequences.

[AM23] concluded that VR training led to measurable improvements in teachers' ability to manage classroom challenges by enhancing classroom control, improving lesson delivery, boosting confidence, and reducing anxiety. According to the review of [HRKR21] over the VR teacher training education from 2010 to 2020, most studies (over 95% in 46 studies) reported positive outcomes, confirming that VR is an effective training tool. Given these significant benefits, leading applications of XR have emerged to support teacher training. The following are some notable examples and their feedback mechanisms.

1.3 Teach-R framework with Unity and CoachVR

Introducation to the framework

Teach-R is a Unity VR application for teacher education that was originally started at University of Potsdam (cf. [WRZR19]). It provides an immersive and interactive learning environment suitable for training in stressful situations.

Specific scenarios can be created to simulate various teaching challenges (cf. [HS23]), as one of the important purposes of Teach-R is to train teachers in classroom management. A key advantage of Teach-R is its capacity to simulate chaotic classroom scenarios in a controlled manner, while also enabling such situations to be reproduced with ease. Teach-R simulates the (mis)behavior of students and is used to teach classroom management. For instance, students can raise hands, have small talks, throw paper balls, e.g.

The system is now able to capture and analyze teacher gaze behavior and reaction times, requiring them to prioritize tasks under time constraints (cf. [HS23]). Several rooms have already been developed, including a chemistry room, a computer lab, and standard classrooms with various seating plans. Accordingly, student (mis)behavior also shows slight differences across different types of classrooms.

For better setting of scenarios, the instructor will control students' behavior in the classroom via web application CoachVR[1]. However, the link provided here is not the same as the CoachVR we are currently using, so the older version is included here merely as a reference to help with understanding the functions of CoachVR. We intend to rebuild CoachVR with React.js, so the new version CoachVR is currently not directly reachable via public websites.

Figure 1.1: The VR view of the teacher trainee (left) and the coach on the desktop website (right)

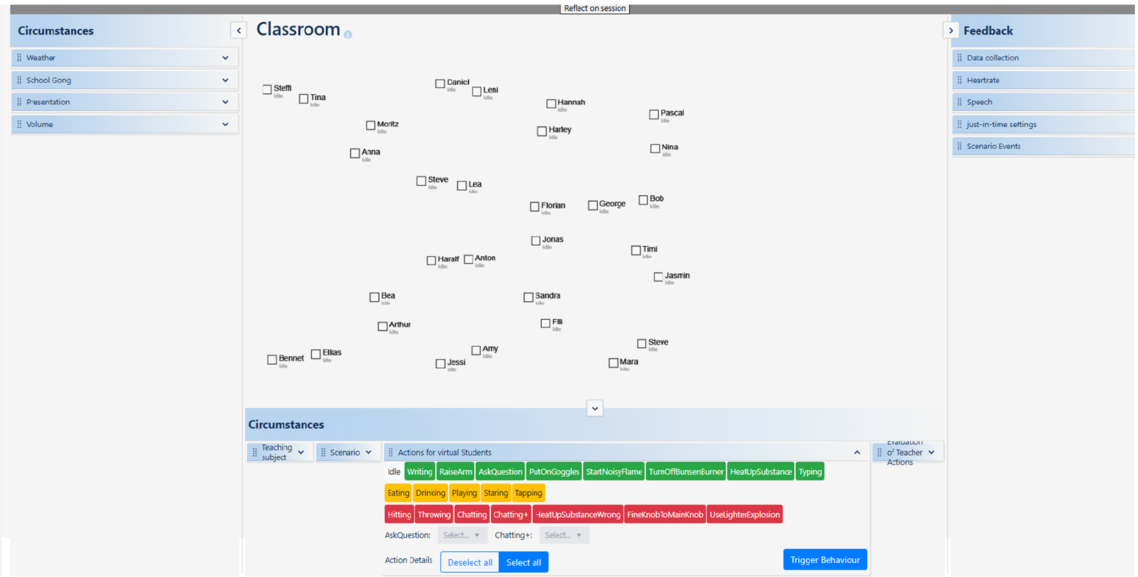

Figure 1.2: The new React CoachVR control page

1.4 The Polar Heart Rate Sensor

Introduction to the Polar H10 heart rate sensor and its usage method

The heart rate sensor we selected is Polar H10 Heart Rate Sensor [2]. As the description writes, the Polar H10 can monitor heart rate with good precision and connect heart rate to a great variety of training devices with Bluetooth® and ANT+.
The connection to Unity can be done via smartphone application Hyperate or Hyperate web service [3]. Before connection, users need to attach the sensor to their chest and ensure consistent contact between a heart rate sensor and the skin.
This process may demand multiple sensor placements. To facilitate quicker sensor performance, it is recommended that users gently moisten the sensor contact areas prior to use. When the sensor is reported to be found by smartphones or websites, users can start the heart rate monitoring session and stop whenever they want.

1.5 The Tools in Learning Analytics

Introduction to Learning Analytics

Based on [Eli11], one key feature of learning analytics is real-time data collection and processing, which aims to capture user interaction data and to process and analyze data continuously with minimal time delay based on live user performance. Another key feature is personalized learning adjustments, which aims to give real-time hints and customized learning path.

Introduction to xAPI and how xAPI works

In our learning environment, we need a way to format and record data. xAPI, also known as the Experience API or Tin Can API, is an IEEE approved standard for learning technology that makes it possible to collect data about the wide range of experiences a person has (cf. [Sof25]). This API captures data in a consistent format about a person or group's activities from many technologies.
Here is a general description of how xAPI works (cf. [Sof25]):

[1] See *CoachVR Classroom* at `https://stage.coach-vr.elearn.rwth-aachen.de/control/classroom`.
[2] See *The Polar H10 Heart Rate Sensor* at `https://www.polar.com/en/sensors/h10-heart-rate-sensor`.
[3] See *The Hyperate Team Web Service* at `https://www.hyperate.io/webbluetooth`.

- People learn from interactions with other people and content. The actions can be any events where learning can occur and can be recorded with xAPI.
- When an activity needs to be recorded, the application sends secure statements in the form of “Noun, verb, object” or “I did this” to a Learning Record Store (LRS.).
- Learning Record Stores record all of the statements made. An LRS can share these statements with other LRSs.

Introduction to OmiLAXR and its advantage

Data collection is the first step in learning analytics. In current Teach-R version, the pipeline of OmiLAXR (cf. [GHS24]) is used to collect and store data. The tool can be utilized to monitor various game objects and gather valuable data from Unity.
Even for smaller data collections it may be an overhead, the integration of OmiLAXR in Teach-R brings many advantages:

- TeachR is planned to use OmiLAXR for other LA use cases. Using it directly, make the code plug-and-play reusable.
- OmiLAXR targets standardization and unification of data collection of MMLA and XR. Using OmiLAXR the data will be standardized.
- Using OmiLAXR directly, will potentially generate a huge amount of data. This way it will generate data additionally to the own created.
- OmiLAXR is using plug-and-play HypeRate plugin (OmiLAXR.HypeRate).
- Using OmiLAXR’s HeartRateProvider, your code will be independent from any heart rate SDK. By exchanging it, your code should still work.
- Following OmiLAXR modular design, you create FAIR software artifacts.

As for processing and analyzing data, Teach-R already integrated visualizations of focus, step, and position. For objective assessment of classroom management in Teach-R, [Har24] already provided an objective feedback about their classroom management skill by visualizing data collected from Unity Engine. Additionally, [Rec25] used real-time visualization and feedback on voice usage via VR visualizations. The speech and voice analysis could help teachers manage their vocal health in classroom management.

1.6 Concept of Data Visualization

Data visualization transforms data into more easy-to-understand forms. VR has been promoted as a tool to simplify design, engineering, construction, and management for built environments due to its sophisticated immersive and interactive visualization capabilities (cf. [LTW+18]).

Traditional visualization techniques refer to methods for visually presenting complex datasets to reveal patterns, relationships, and trends that may not be obvious in raw data (cf. [BI23]). These techniques convert data into visual elements like points, lines, bars, and areas, which are then arranged into common formats such as bar charts, scatter plots, pie charts, histograms, graphs, and tables. These visualizations are powerful tools for data exploration, analysis, and communication. When people see visual representations of data, they naturally associate data attributes with visual properties such as position, length, color, or shape. This enables them to intuitively interpret information, spot patterns or anomalies, and make informed decisions, even uncovering insights that might not be immediately obvious (cf. [BI23]). More techniques have been developed for visualizing different types of information over the last few years. One example is immersive data visualization, it is an easy-to-use technology that turns 3D BIM (Building Information Modeling) models into engaging spatial experiences of design that participants can explore. Another example is immersive analytics, it is the use of engaging, embodied analysis tools to support data understanding and decision making. Immersive analytics builds upon the fields of data visualization, visual analytics, virtual reality, computer graphics, and human-computer interaction (cf. [ILQC18]).

Chapter 2 Related Work

2.1 Presence and Physiological Measurement in VR

The term presence

The term presence is a concept of philosophy. Research (cf. [WH24a]) indicates that the presence experienced in VR environments enhances user satisfaction, reduces errors during tasks, and promotes more enduring training effects. The authors describe presence in the VR context as the sense of "being in the mediated world" and they also note that the feeling of presence of is not only related to the feature of the VR environment itself, but it may also have connection with the personality, abilities and demography of VR users.

2.1.1 The Evaluation Methods of Presence

Evaluation of Presence: Implicit Method and Explicit Method

Regarding the evaluation of presence, this paragraph summarizes the study review of Halbig (cf. [HL21]). Current methods of measuring presence can be broadly divided into two types: explicit method that requires active expression from the user, and implicit method that requires no extra effort for the user. The explicit method mainly takes the form of questionnaires and interviews, while the implicit method mainly consists of physiological measurements monitored by the sensor and observations in the form of quantitative data. The authors further note that the use of explicit methods in surveys comes with several drawbacks. For instance, response biases can affect how people answer questions, and it is difficult to know whether participants truly understand them. Moreover, the reliability of such methods depends on an accurate recollection of experience. The same study further points out that implicit evaluation methods help overcome these limitations, with physiological measurements providing decisive advantages. For instance, by using implicit methods, they can analyze the user behavior based on the response to a certain stimulus or event and they are able to avoid relying on the ability of subjects to assess participants' condition.

Regarding the usage trends of the physiological measurements sensor itself, according to the review of [TSR25], the sense of presence measured by sensors is a critical research area in virtual reality. The review concludes multisensory feedback, the expression of emotion and new technologies such as light detection can improve the sense of presence. Their review also summarizes the most frequently monitored part is the upper body and the placement of sensors is designed to to minimize interference with natural movements in VR, namely: head and hands, facial muscles, and torso (e.g., ECG sensors for heart rate variability).

2.1.2 Real-Time Feedback in VR Systems

Feedback can be given via real-time and asynchronous feedback and both are important because they are used in this thesis, therefore we will take a look at how real-time feedback can be given in VR and how this has been adopted, also in regard to the feeling of presence. Real-time feedback is an important part in contributing users' experience and presence need in VR systems. Computerized interfaces with customizable visual, audio, and haptic modules provide greater flexibility for delivering enhanced sensory feedback (cf. [SCL+22]).

Which Real-Time Feedback is Effective?

As commonly highlighted in VR research, feedback can be classified according to the sensory channel involved, namely visual, haptic, and auditory (cf. [SCL+22], [GGP22]).

For an immersive VR setup, researchers need to know which effective interaction is more suitable or natural in the case of the specific 3D situation (e.g., visual or audio) (cf. [SCRJ23]). Moreover, there is an urgent need to understand how different modalities work together to improve the user experience (cf. [GGP22]). The study reports an experiment that explores the contributions made to participants' sense of presence by haptic and visual feedback in a virtual environment. The finding notes that bimodal feedback enhances presence compared with haptic or visual alone, visual alone does not give a better sense of presence than haptic alone, and varying the location of events enhances presence regardless of feedback modality.

In one study (cf . [SCRJ23]), results are expected to provide guidelines on how to focus on constructing educational VR content. Researchers investigated the effects of a few interaction responses on the participants' perceptions of interest, understanding, preference, and remembering. They focused on the perception of learning effects, and it was found that the interaction feedback of a deformable object improved the participants' perception of educational effect. Also, participants in the study reported that the audio response was most effective in the case of remembering.

Consideration for Providing Feedback

These considerations highlight that not only the technical accessibility of VR systems but also the design of feedback itself plays a crucial role in determining user performance and experience. Sanford stated that simpler feedback generally produces better performance, whereas complex feedback may cause cognitive overload (cf. [SCL+22]). Moreover, Sanford further noted that simpler feedback is associated with higher physical arousal, drawing on earlier studies (as cited in Bannert, 2002; Critchley, 2002).

Example: Visualization Feedback In VR Helps Learning

Prior research suggests that visualization feedback can support learners in grasping abstract concepts more effectively. For instance, a study was conducted in an introductory university physics course at a Mexican university, focusing on the role of VR in teaching vector concepts (cf. [CHZ22]). Students in the experimental group used PC-based VR equipment and the software Gravity Sketch to manipulate and visualize vectors within a three-dimensional grid while completing preassigned team activities, while the control group did not use VR. Learning performance and VR perceptions were evaluated using pre and post-questionnaires, as well as a perception survey. The results show that VR provides significant benefits for learning tasks that involve the visualization of content, with the experimental group outperforming the control group in problems involving angles and components. Although VR does not enhance learning for all types of content, students generally recognized its positive impact on their experience, even when its use was not tied to course credit. Some students focused more on the technology itself, and a few attributed learning difficulties to VR, but overall VR improved understanding of abstract concepts and supported motivation.

2.1.3 Heart Rate as a Presence Measurement Method in VR

Among 78 studies on VR presence between 2001 and 2025, 40% of them utilized ECG as a heart rate monitoring sensor (cf. [TSR25]). As heart rate monitoring is a key physiological measurement in the study of presence in VR. The following part presents several example studies on heart rate in VR.

Heart rate in odor system

In one study (cf. [AKH+24]), heart rate was measured together with other signals (like PPG, ECG, and SCR) using different sensors such as Shimmer, Polar H10, and Empatica E4. Several sensors were used at the same time to reduce noise in VR and to compare different sensor placements. Although the main goal was to test the odor system, heart rate was still an important measure of stress, showing that future VR stress training for emergency workers can include it to check training effects.

Heart rate during food intake in VR

In another study about food intake (cf. [OH21]), heart rate was monitored as a physiological marker of presence and emotional arousal during eating in VR. Participants showed a modest increase in HR when eating in the restaurant scene compared to the blank scene (79 to 83 BPM), suggesting some effect of the virtual environment on arousal. However, the effect size was small, and no significant correlations were found between HR and food intake or masticatory parameters, indicating that HR changes were limited mainly to reflecting presence rather than influencing eating behavior.

Heart rate during food purchasing in VR

In another study focused on food purchasing behavior (cf. [WH24b]), heart rate was measured together with electrodermal activity using surface electrodes. Both indicators were higher when participants experienced the immersive VR supermarket and restaurant scenes compared to the PC-based versions, suggesting that VR triggered stronger physiological arousal. The authors highlight that such physiological markers, including heart rate and potentially heart rate variability, can serve as objective measures of presence, overcoming some of the limits of self-report questionnaires. They also suggest that future work could extend this approach by examining links between heart rate responses, endocrine or metabolic markers, and food-related decision-making in VR.

Heart rate and height exposure

In a study of fear in virtual reality height exposure (cf. [GRCP19]), heart rate was recorded as part of the physiological responses to the virtual height scenario. Higher heart rate, together with increased skin conductance, indicated stronger arousal, which in turn was linked to greater presence. This supports the idea that arousal, reflected in physiological measurements like heart rate, plays a key role in shaping the sense of presence in VR.

2.1.4 Conclusion for Heart Rate as a Physiological Measurement

Heart rate is an objective measurement of VR experience engagement

Relying only on questionnaires to assess presence in VR has drawbacks, since they are subjective and participants' memories may be inaccurate. Heart rate gives a simple and objective way to see how engaged people are in VR. When heart rate goes up, it usually means stronger arousal, which is often linked to feeling more "present"

in the virtual world. It helps capture what's going on beyond what people just say in questionnaires. As presented in **Section 2.1.3**, it does not mean that we should overlook the role of questionnaires. A study (cf. [WPH+25]) recommends keeping questionnaires as an important tool for capturing subjective experience, while combining them with physiological data to gain a more complete understanding. The study further notes that since presence also depends on individual perceptual–motor styles, group averages can be misleading, making longitudinal monitoring of individuals valuable. Finally, as the authors pointed out, larger and more standardized studies are always needed to ensure reliable and comparable results.
In many VR settings—such as stress training, eating behavior, shopping, or height exposure—heart rate is often used as a clear sign of arousal and is linked to how present users feel in the virtual environment. Classroom management is naturally stressful, so heart rate can serve as a useful signal of teacher arousal and engagement. Adding HR feedback to Teach-R builds on this known connection between arousal and presence in VR, while also making it a practical tool for helping teachers train and manage stress.

2.2 Biofeedback (BF)

Introduction to Biofeedback

Biofeedback is a technique that helps people manage body processes once thought to be beyond voluntary control and is commonly used in healthcare to manage disease symptoms as well as to improve overall health and wellness through stress management training (cf. [FKK+10]). [LF22] describes biofeedback as such a process: Instruments record physiological signals (e.g., heart rate, breathing, muscle tone, skin temperature) and return the information to individuals through visual or auditory channels. At last, by means of biofeedback, users, much like children learning to read and write, gradually acquire self-regulation skills (cf. [GVMS+16]).

2.2.1 Biofeedback Methods

Introduction to BF

Many existing academic research on biofeedback is situated within the medical domain. For instance, biofeedback has been applied in the treatment of tension headaches and chronic pain, as well as in reducing sympathetic arousal (cf. [FKK+10]). In a review of chronic pain rehabilitation biofeedback, the article summarizes biofeedback can be implemented by following common methods ([CMD+25]):

- Electromyography: A diagnostic technique to assess the health and functioning of muscles and the nerve cells that govern them by detecting electrical activity in skeletal muscles.
- Thermal Biofeedback: A method that helps people learn to manage involuntary physiological processes like skin temperature.
- Electrodermal Biofeedback: A technique that measures the electrical conductance of the skin, which varies with its moisture level.
- Neurofeedback: A therapy approach that teaches self-regulation of brain function by displaying brain activity in real time.
- Heart Rate Variability: A measure of the variation in time intervals between successive heartbeats

2.2.2 Two-Dimensional Biofeedback(2D-BF) and VR Biofeedback(VR-BF)

The Barriers in Biofeeback Area, especially 2D-BF

The biofeedback provided to users can include Two-Dimensional Biofeedback (2D-BF) and Three-Dimensional Biofeedback (3D-BF). The media of 2D-BF can be standard visual diplay on a 2D monitor. However, stimuli used in classical anxiety treatment have been regarded as quite abstract, complex, or not appealing to patients, hence, leading to low motivational levels and difficulties of keeping up training (cf. [KGB+22]). This finding is consistent with the results reported by [GVMS+16], the study further notes that motivation may stem from external sources (e.g., a pat on the back, or food) or be intrinsic when driven by self-motivation. The authors suggest that a plausible approach is to base the reinforcement signal on intrinsic motivation, allowing users to achieve a balance between task difficulty and skill proficiency, which in turn engages voluntary attentional processes and higher cognitive functions. As Ryff noted, it is well-known that human interactions are catalysts of intrinsic motivation (cf. [RK95]). Nevertheless, the authors still argue that the biofeedback paradigm is still too often based on solitary human–computer interactions (HCI), with the 'human variable' rarely examined.

The effectiveness of VR-BF compared to traditional BF: It is to be further investigated

Virtual reality has become a transformative tool that revolutionizes many research areas, as VR technology developed and the introduction of more precise sensors for motion tracking, along with enhanced display quality, helped close the gap between digital and physical experiences. (cf. [FLE+25]). In the context of biofeedback, virtual reality systems inherently support the real-time requirements of biofeedback applications, as they combine environments with immediate interaction.

With respect to comparing the effects of 2D-BF and VR-BF, [KGB+22] concludes virtual reality biofeedback interventions seem to be a promising augmentation of traditional 2D-BF for treating anxiety symptoms. For instance, a study(cf. [BRG19]) tested whether a virtual nature environment could enhance heart rate variability biofeedback (HRV-BF) with slow-paced breathing compared to standard HRV-BF in a randomized controlled trial with 60 employees. While both approaches showed similar physiological outcomes, the VR-based HRV-BF was more effective at reducing perceived stress after a cognitive stressor, boosting relaxation self-efficacy, decreasing mind wandering, and supporting present-moment focus and attentional control. These findings highlight the added psychological benefits of immersive VR contexts, although future studies are needed to examine long-term effects and broader applicability.

traditional BF and VR-BF: it seems they are equally effective

However, the positive effects of VR do not seem to translate into an advantage of VR-BF over classical BF in terms of effectiveness in a short-training session (cf. [LF22]). They remark that one reason may be that the motivational aspects emerge only after several training sessions. They argue that further research comparing long-term training with VR-BF and traditional BF is needed to determine whether VR offers added benefits over conventional protocols or VR is better suited as a complementary therapy. This possible reason is supported by the findings of [GVMS+16], classical BF as well as VR-BF may both profit of the novelty effect, but over time the abstract, traditional BF tasks may make it difficult keep up attention and motivation.

Similarly, according to [CMD+25], no between-group differences were observed, indicating that their fully immersive, gamified VR-BF treatment was equally effective to standard 2D-BF, contradicting their initial hypothesis of greater efficacy of VR-BF.

Yet, a study [KWN+23] has provided a preliminary evidence that VR technology is suitable for HRV-BF training in laboratory sessions. The benefits observed are similar in size to those reported in studies using two-dimensional screens for HRV-BF. Yet, as mentioned in their discussion of limitations, the novelty and placebo effects of VR-BF remain to be addressed.

2.2.3 Study of Heart Rate Biofeedback in VR

Nevertheless, some studies on biofeedback have taken advantage of the convenience offered by VR systems, especially in research on heart rate.

Example: HRV Biofeedback Stduy in VR among young paitents

In a study of young patients with stress related disorders (cf. [EGH+25]), the VR-based biofeedback application *Conquer Catharsis* places users on a virtual island that can be explored through full-body tracking and handheld controllers. Progress in the environment is linked to biofeedback tasks: users must reduce their heart rate below a set threshold for 10 seconds to complete mini-games, such as raising a submerged platform to cross water. Across eight mini-games, relaxation becomes the key to advancement in the scene, the progress is lost if heart rate rises again. The study was generally effective in reducing stress and anxiety across various disorders. However, the authors' assumption that VR, combined with gamification elements, as applied in their study, would particularly benefit children by enhancing motivation and attentional focus was not supported. Participants in both the VR-BF and 2D-BF groups rated their treatments as equally enjoyable, engaging, and helpful.

Example: HRV in VR and Breath Control

Another heart rate biofeedback study is about the breath control in VR [DCL+24]. The study recorded participants' cardiac activity using pulse PPG and respiration with a chest belt. After a 5-minute baseline, participants completed two VR tasks. The first was a training game designed to teach paced breathing to lower heart rate, with biofeedback provided via visual cues. The second was a stressor game in which success depended on keeping heart rate low to avoid detection by a virtual creature. Heart rate thus functioned as the key physiological signal guiding both training and stressor outcomes. This study showed that VR-based biofeedback training effectively enhanced HRV. Overall, the findings support the potential of VR biofeedback to promote autonomic control through slow-breathing techniques.

Another Study of Breathing Control/HR biofeedback in VR, the Placebo Effect is Examined

Similarly, in Chittaro's study (cf. [CSV24]), breathing control and heart rate were examined through biofeedback in VR. The VR experience was designed into five phases, the phases begin with breath measurement and moving through relaxation and small interactive tasks. A voiceover guided users to focus on elements of the scene, while their breathing subtly influenced the environment, and the session ended with a rewarding scene designed to promote relaxation and engagement. In the third phase, heart rate was represented by fireflies whose glow intensity was directly mapped to heart rate activity, providing an intuitive feedback channel inspired by video game techniques that link visual rhythm to heartbeat cues. The results showed that the proposed system helped participants to relax. Moreover, the study also examined the placebo effect, and the authors pointed out that the real biofeedback led to greater relaxation as well as greater sense of presence than sham biofeedback (placebo biofeedback).

A VR Biking Game Study

Even more approaches to reflect heart rate changes in a biking exergaming study in VR (cf. [HWO+25]), four groups of visualization were created for biker racing in the spring forest. The first group is the change of environment. The visualizations use dynamic changes in atmosphere and environment to signal deviations from the target heart rate zone, encouraging users to regulate their effort and return to optimal conditions. The second group is distortion of reality. These distortion effects use motion blur and color saturation as intuitive cues to reflect the user's heart rate zone, guiding them to maintain optimal intensity by visually linking pace and effort with environmental feedback. The third group is gamification. Through the use of Non-Player Character (NPC) pacing and collectible rewards, this design gamifies heart rate regulation by offering clear visual cues and incentives that encourage users to stay within the target zone. The fourth group is visual overlays.By combining immersive frame effects and a color-coded GUI scale, this approach provides both experiential and informational cues to help users monitor and adjust their heart rate within the target zone, while also highlighting opportunities to refine GUI design for VR.

How does it help

The study shows that real-time adaptive visualizations, particularly Adaptive NPCs, help users regulate heart rate more accurately and spend more time in the target zone without raising perceived exertion. While motivation and enjoyment were not significantly enhanced across all conditions, results indicate that adaptive designs are more effective than static or random NPCs in sustaining intrinsic motivation. Overall, these findings highlight the potential of adaptive visual feedback in VR to support both precision training and user engagement.

2.2.4 A Conclusion of Current Biofeedback Study

Conclusion of Current VR-BF Study

Taken together, current studies indicate that VR-BF is feasible and may enhance motivation compared to traditional 2D-BF (cf. [CMD+25]). However, findings from short-term training sessions reveal no consistent superiority of VR-BF, and both approaches may be influenced by novelty and placebo effects (cf. [KGB+22]). At present, no strong evidence supports VR-BF as more effective than traditional BF, highlighting the need for long-term, well-controlled studies to determine whether VR-BF provides genuine benefits or should be regarded primarily as a complementary tool (cf. [LF22], [GVMS+16]). In any case, across these studies, the effects of VR-BF were at least equally effective to those of traditional BF [CMD+25]. Some studies employing VR-BF confirmed its effectiveness, at least by contrasting it with placebo effects (cf. [CSV24]).

2.3 Human-Computer Interaction (HCI)

Introduction to HCI

Human-computer interaction (HCI) is the study of the ways people interact with and through computers (cf. [Sha96]). HCI seeks to address the growing industrial and societal need for advanced education and research focused on making computer-based systems more human-centered(cf. [CKCX+21]). When applied to VR, these principles translate into the design and use of specific hardware and software technologies that enable more natural, immersive, and effective interactions.

HCI principles

Unless otherwise noted, the following content in this section is cited from Zeng's summary [Zen24]. In VR scenarios, commonly used HCI hardware includes VR headsets, controllers, and sensors, with additional devices such as eye-tracking systems further enhancing the immersive experience. In VR, key software technologies enable natural and immersive HCI. 3D modeling provides the foundation for creating realistic environments and objects. Motion capture tracks users' movements in real time, allowing natural actions like walking or gesturing. Speech recognition adds verbal interaction, enhancing realism and collaboration. Together, these technologies are essential for VR interaction, and their continued development will further expand applications and enrich user experience.

HCI Challenges

To better understand how these hardware and software components shape user experience, it is also necessary to consider the challenges and design principles that guide effective HCI in VR. As Zeng notes regarding the challenges of HCI in VR, improving interaction requires reducing operational complexity and cognitive load. This can be achieved by designing simplified, intuitive interactions aligned with users' needs and habits. Interfaces should remain clear and uncluttered to minimize distraction, while artificial intelligence (AI) can enhance the experience by analyzing user behavior, predicting subsequent actions, and providing intelligent prompts that support task completion more efficiently.

In conclusion, as Katona's review notes [Kat21], integrating HCI with 3D VR environments can enhance cognitive performance, foster creativity, and support innovative knowledge acquisition tailored to individual abilities. However, Katona also emphasizes that users are often slow to adapt to innovation, and the effectiveness of new interfaces depends on a clear understanding of their limitations.

2.4 Heart Rate Variability as a Stress Indicator

heart rate can measure teachers' stress

Current learning analytics provide valuable insights into teacher performance through data collection and processing, based on key findings from mentioned research, they primarily focus on cognitive and behavioral aspects such as speech patterns, gaze tracking, and classroom engagement. These factors could be good factors to analyze the performance of trainees. Furthermore, effective teaching also demands emotional resilience and stress regulation (cf. [Har20]). Stress is the body's natural response to challenges or demands, often manifesting as physical, emotional, or mental strain (cf. [Sel36]). [Qin24] suggests that higher stress levels among instructors can lead to lower student engagement, decreased academic performance, and negative teacher evaluations. To address this, heart rate monitoring can emerge as a physiological data source that complements learning analytics by providing objective stress measurements.

Teacher stress scale

Objectively assessing teachers' stress levels is a challenging task. Most studies do not offer objective feedback on stress level of teacher trainees. The most commonly used method to measure teacher stress is through self-report surveys. Some well-known scales include:

- Teacher Stress Inventory (TSI): Includes items about workload, student misbehavior, time pressure, and lack of support (cf. [Fim84]).
- Maslach Burnout Inventory (MBI): Evaluates teacher burnout, measuring emotional exhaustion, depersonalization, and reduced personal accomplishment (cf. [MJL96]).
- Classroom Appraisal of Resources and Demands (CARD): Assesses teachers' perception of classroom demands versus available resources (cf. [MLF09]).

According to [FSBMG14], some studies also use direct classroom observations to evaluate stress-related behaviors, such as: Facial expressions and body language, voice tone changes (e.g., raised voice, hesitation), and behavioral patterns (e.g., pacing, fidgeting).

Other key factors of teachers' stress

Some researchers also turn to other factors as the key indicator of stress, [SA15] did not directly measure stress levels but rather assessed classroom management skills. The study found that student misbehavior is a significant stressor for teachers, particularly in high schools where adolescents exhibit more challenging behaviors. This point aligns with the findings of [LGRM08] on classroom management: The study reveals that teachers with strong classroom management skills experience lower stress levels, as they can handle student behavior more effectively. Additionally, teachers who have taken classroom management courses or read books on the topic feel more prepared and experience less stress (cf. [İl07]). However, it is still a questionnaire-based survey.

In the recent decade, researchers have started using objective physiological indicators of stress (cf. [FSBMG14]):

- Heart Rate Variability (HRV): Increased heart rate and lower HRV indicate higher stress levels.
- Cortisol Levels: Collected through saliva samples, cortisol levels are higher when teachers experience chronic stress.
- Electrodermal Activity: Measures changes in skin conductance, which reflects emotional arousal due to stress.

Heart Rate Variability (HRV) measures variability in the time interval between heartbeats. According to [KCB+18], HRV is a valid and objective measure of psychological stress. [FARBG16] used Heart Rate Variability (HRV) as a key stress indicator to assess short-term mental stress. It confirms the correlation between HRV frequency power ratios and stress intensity and develops a model for predicting HRV under stress. HRV analysis has been applied in various training settings, including medical education, sports performance, and emergency response training. [FBR+23] used wearable HR sensors to track how students' heart rates changed during different teaching activities, suggesting that a similar approach could be applied to teacher trainees. [HRKR22] found that larger class sizes in VR classrooms led to significantly higher heart rate and perceived stress levels of teachers. Interestingly, in the study of [WRLH24], trainees were required to write down detailed reflections after each session, researchers found more frequent use of these words ("I, me, my") was linked to higher stress levels during teaching. This aligns with the findings of the HR part of the study. however, HR data is available for only a subset of participants in this study. [BC23] examined HRV and perceived stress in teacher trainees, demonstrating that new teachers experience “reality shock,” with stress levels decreasing over time.

Reasons for using heart rate visualization

In our study, we focus on heart rate rather than heart rate variability (HRV). Since HRV is not only influenced by autonomic nervous system activity but also mathematically dependent on heart rate due to the inverse relationship between RR intervals and heart rate (cf. [Sac14]). The authors state HRV analyses can be biased when individuals differ in their baseline heart rate, unless corrected through complex normalization procedures. Heart rate, by contrast, provides a more direct and robust physiological indicator that avoids such mathematical confounds. Moreover, given that HRV is difficult for non-experts to interpret, presenting heart rate directly is more intuitive and accessible in non-medical contexts. HRV remains a valuable analytical tool and can be processed in the background to provide more in-depth insights into users' physiological states without requiring them to interpret complex metrics.

2.5 Training for Stress Management of Teachers

2.5.1 self-efficacy and stress

Introduction to self-efficacy

The concept of self-efficacy was introduced by Bandura (1977, as cited in [TMH07]) as an assessment of one's belief in their ability to achieve a desired level of performance in a specific task. Teachers who doubt their ability to succeed with certain students often put in less effort, give up quickly when challenges arise, and may not use helpful strategies they already know (cf. [TMH07]).

Insufficient self-efficacy can leat to stress

Teaching is a challenging profession, and teachers experience stress due to the difficulties associated with shifting educational policies, disengaged or dissatisfied parents, and the behavioral, emotional, and academic needs of diverse students. This stress often contributes to increased burnout and reductions in self-efficacy, as prolonged stress may result in burnout, understood as the gradual build-up of job-related stress that undermines professional performance. (cf. [AV24]). Similarly, Skaalvik notes (cf. [SS16]): "For teachers, low levels of self-efficacy (i.e., negative beliefs about their abilities to succeed in teaching and managing their students) can lead to low levels of satisfaction with the profession" . In light of these challenges, professional development training has been emphasized as an important support mechanism: "In the ever-evolving educational space, professional development training plays a pivotal role in empowering teachers with the knowledge and skills required to enhance their instructional practices and improve the quality of education. Importantly, professional development training programs have long been recognized as catalysts for improving teaching quality and student outcomes" (cf. [SLA24]). Overall, all stakeholders involved in the current research acknowledged the impact of emotional and physical demands on educator stress management well-being (cf. [ZPB+24]).

2.5.2 Different Training Approaches

Different training approaches have been explored to determine their effectiveness in reducing teacher stress and enhancing self-efficacy.

Study: SEL

One framework that connects professional development with teacher well-being is Social and Emotional Learning (SEL), which provides both practical coping strategies and a broader developmental foundation. According to the Collaborative for Academic Social and Emotional Learning (2013, as cited in [ZPB+24]), SEL is a comprehensive framework that emphasizes self-awareness, self-management, social awareness, relationship skills, and responsible decision making in educational contexts. As noted in Zito's study, integrating stress management training into teacher preparation aligns closely with the principles of SEL. Positioning stress management within the SEL framework not only equips pre-service teachers with practical coping strategies for professional challenges but also provides a broader developmental foundation that enhances their resilience, well-being, and long-term sustainability in the profession [ZPB+24].

Study: CL

Building on this, specific instructional approaches such as cooperative learning (CL) have been examined for their potential to simultaneously enhance teacher efficacy and reduce stress. In Anton's Study (cf. [AV24]), it demonstrates that CL, a student-centered instructional approach where small groups work together under conditions of positive interdependence and individual accountability, when supported by Peer-Learning.net, can play a meaningful role in reducing teacher stress and burnout while enhancing self-efficacy. Although the effects did not extend to all domains, the improvements in emotional exhaustion, personal accomplishment, student engagement, and instructional strategies point to clear benefits for teacher well-being. When paired with prior evidence of CL's positive impact on student outcomes, these findings suggest that CL represents a promising instructional approach with the potential to benefit both teachers and students.

Study: TPD

Similarly, research on Teacher Professional Development (TPD) highlights that training programs are most effective when they integrate resilience-building strategies alongside instructional improvement. In Shakimova's examination review(cf. [SLA24]), the study shows that TPD works best when it includes resilience-building strategies. Traditional TPD often focuses on improving teaching skills but tends to miss the personal and contextual challenges that create stress for teachers. Adding resilience elements can ease job-related stress, help teachers handle professional demands, and improve their overall well-being, especially for female teachers. While years of service do shape resilience, resilience-focused TPD (TPD-R) can boost and speed up this ability no matter a teacher's experience level. Overall, the findings suggest that TPD should be designed not only to improve classroom practice but also to give teachers the support they need to stay healthy and sustainable in their careers.

2.6 Teacher Training Application

VR Training is a safe place for teachers to make mistakes

VR teacher training offers risk-free, immersive learning environments with immediate and detailed feedback on verbal and non-verbal interactions (cf. [AMRH+24]). According to [GG20], traditional classroom placements are high-pressure environments, leaving little room for experimentation. Additionally, mistakes in traditional classrooms can lead to loss of classroom control, credibility issues with mentor teachers, or missed learning opportunities. In contrast, teacher training in VR can create a safe space for trial and error, providing feedback without severe real-world consequences.

VR training effect is positive

[AM23] concluded that VR training led to measurable improvements in teachers' ability to manage classroom challenges by enhancing classroom control, improving lesson delivery, boosting confidence, and reducing anxiety. According to the review of (cf. [HRKR21]) over the VR teacher training education from 2010 to 2020, most studies (over 95% in 46 studies) reported positive outcomes, confirming that VR is an effective training tool. Given these significant benefits, leading applications of XR have emerged to support teacher training. The following are some notable examples and their feedback mechanisms.

Breaking Bad Behaviors (BBB)

Introduction to BBB and its feedback mechanism

Developed by (cf. [LLH+16]), Breaking Bad Behaviors (BBB) is a virtual classroom management training environment that provides realistic student behaviors, allowing teachers to practice handling disruptive behaviors. In the system, the instructors control the students' actions. They can control the overall disruption level(Null, Low, Mid-Level, High, Extreme) for the entire class, trigger specific behaviors or dialogues for individual students, or automate student responses using a behavior tree. If trainees fail to intervene correctly, the disruptive level will escalate.

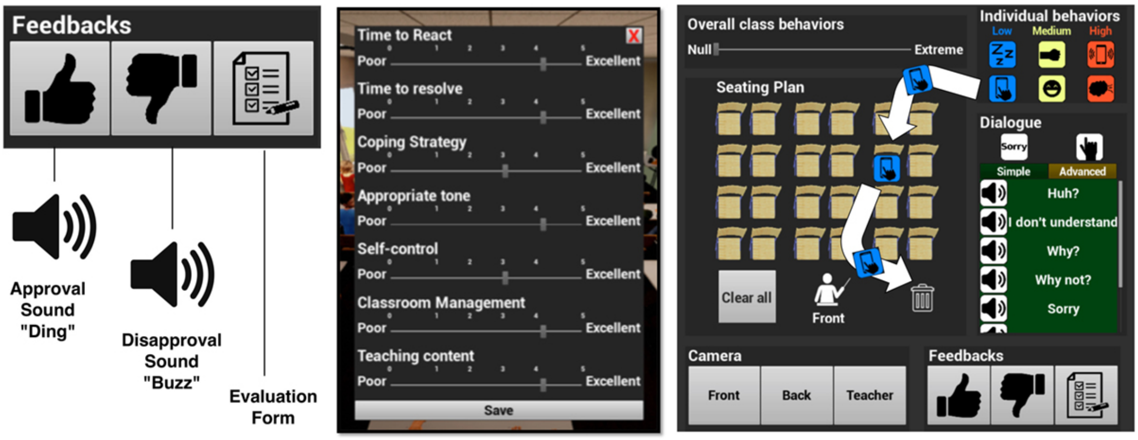

Figure 2.1: Feedback and control mechanisms in BBB (cf. [LLH+16])

Synchronous Feedback: The Thumb-Up and Thumb-Down buttons provide immediate feedback to the teacher trainee during the session (manipulated by human instructors).

- Thumb-Up Button: When pressed, the trainee hears a ding sound, signaling instructor approval for a well-suited classroom management decision.
- Thumb-Down Button: When pressed, the trainee hears a buzz sound, indicating that their response to student behavior was ineffective or not.
- Mute Option: Instructors can enable or disable the feature if they believe it is affecting the teacher's immersion or concentration. With this button, the system can avoid interrupting the training.

Asynchronous(Post-Session) Feedback: In addition to real-time and human instructors' feedback, the system also provides performance analysis, such as the time taken to respond to disruptions. Trainees can also review video recordings to self-analyze their tone of voice and body language.

TeachLivE™ (TLE)

Introduction to TLE and its feedback mechanism

TeachLivE™ (TLE) is a mixed reality environment and began as an idea created when one of the authors was given a semester to think with colleagues across campus about a different approach to a problem of interest (cf. [DHH+15]).

During the practice, the avatars' behaviors can be manipulated to create an authentic yet targeted experience. The educator in the simulator's performance can be coded on a specified skill to facilitate coaching. Post-session feedback is completed or a computer summary of performance can be provided by an automated system.

TLE creates authentic interactions, allowing trainees to engage with student avatars in real time through their movements, actions, and discourse. The avatars in TeachLivE embody specific archetypes typified by common personalities that exist in any classroom environment. Real-Time feedback such as verbal and nonverbal cues including verbal reactions, body language and facial expressions from avatars.

Post-Session Feedback: Teachers have the opportunity to review recordings of their simulation sessions, allowing them to self-assess and identify areas for improvement. The system can generate reports analyzing various aspects of the teacher's performance including the frequency of higher-order questioning or the balance between teacher and student talk time.

Didascalia Virtual-ClassRoom (DVC)

Introduction to DVC and its feedback mechanism

Based on [BCDNLG+20], Didascalia Virtual-ClassRoom (DVC) provides animmersive VR experience. Trainees are placed in a virtual secondary school classroom. They must respond to three common disruptive behaviors: challenging teacher authority (e.g., students arguing with the teacher), peer disruptions (e.g., students chatting or distracting others), and group conflicts (e.g., a student refuses to work with a group). The system tracks how trainees respond to disruptions and categorizes their reaction(Proactive, Reactive and Avoidant). The system dynamically responds to the user's actions, including tone of voice, speech content, non-verbal cues, proximity to avatars, and gaze direction. In the post-simulation phase, human instructors play a vital role by facilitating reflective discussions, providing personalized insights, and helping participants translate their virtual experiences into effective teaching strategies.

2.6.1 Feedback Mechanism

Feedback Mechanism is a critical part in educational VR systems. The isolation in VR settings can diminish users' enthusiasm and interest due to a lack of immediate social interaction (cf. [WPH24]).

Conclusion of BBB, TLE and DVC feedback Mechanism

The feedback can be synchronous and non-synchronous. In BBB, real-time feedback is provided in the form of system sound, and in TLE, real-time feedback is provided in the form of the expressions of virtual students, in DVC, after a disruptive behavior occurs, eg., virtual students can come to the teacher and express his or her displeasure with the content of the class. The system evaluates the user's actions by capturing the available parameters before and after a critical incident. The system responds to these inputs (with a decision tree) by triggering different reactions (proactive, reactive or avoidant) in the students. And in the example video of DVC, classroom sound like a burst of laughter is also provided to support feedback [1].

[1] See *The DVC Video Clip at Youtube* at `https://www.youtube.com/watch?v=ghAOEGerz7g`.

From a system-level perspective, post-session feedback in BBB includes system-level generated performance analysis. In TLE, the system can generate a report to analyze performance such as the balance of teacher and student talk time, in DVC, the system always dynamically records and analyzes teachers' action, especially the speech analysis of the teachers. In all 3 systems, BBB and TLE provide recordings of the simulation process, allowing teachers to watch and self-evaluate their own performance. Teach-R currently does not provide functionality for coaches to record their opinions. The coach mainly serves as a scenario controller or takes on the role of a peer reviewer after the session (cf. [Har24].

VR system can use hint to support users

The reward feedback mechanism is also important, as shown in [FFC+25], reward feedback was more effective than no reward feedback in improving behaviors related to attention deficits in children. As described in DVC system, a burst of laughter is counted as a form of reward feedback mechanism in educational VR training.

Summarizing the above three systems, a simple classification of the types of feedback mechanisms can be conclude here:

- Instructor Feedback: A human instructor can monitor the trainee's actions and provide real-time or post-session feedback on the skills of teaching.
- Student Behavioral Feedback: Feedback can be involved with particular target behaviors, such as talking to a student directly or the expression changes of a student.
- Data Feedback: Classroom data of teachers can be recorded and analyzed, such as speech rate, distance to students, and response speed.
- System Feature Feedback: The feature(i.e., voice) of the system can be used as a form of reward feedback to reinforce desired teaching skills.

2.7 Learning Analytics Visualization in Teach-R

Current Teach-R learning analytics visualization

Several 3D visualizations have already been integrated in Teach-R to display different collected data. In Research Focus Class on Learning Technologies(RFC) in 2023 at RWTH Aachen University, data tracking and visualizations have been implemented into Teach-R (as cited in [Har24]): including position, rotation, interaction, and eye tracking as well as the tracking of events on the coach website. Most of the collected information consists of three-dimensional data points or vectors. These data were visualized directly within the VR application: user position was shown through a heat map, eye focus on students was represented with a transparency map, and an advanced scatter plot was created to depict position together with rotation data of the user and their hands (cf. [Har24]).

Visualization of classroom management

As noted before, Teach-R was originally implemented to help teacher trainees practice classroom management (cf. [WRZR19]). Aiming to give an objective foundation for further discussion after a session and for it to be used for self-reflection to aid the user in increasing their sense of self-efficacy, the visualization menu was improved to trigger all visualizations in Teach-R and was further integrated with classroom management visualization by Hartanto in 2024 (cf. [Har24]). The author introduces two scores for each student, describing the student's disturbing behavior (Disturbance Score) and the user's ability to manage said behavior (Teacher Control Score). The

Figure 2.2: Ground Heat Map (RFC 2023 at RWTH Aachen University)

Disturbance Score rises initially when a disturbance begins and again if it affects nearby students, then continues to increase for as long as the disruptive behavior persists. When the user successfully resolves the disturbance, the Teacher Control Score increases. As a result, three distinct visualizations were developed by the author to support classroom management skills:

- Bar Chart: Displays both the disturbance and teacher control score above the student's head as a bar chart. It is described as the least interactive visualization.
- The Radius and Color Visualization: The difference between the teacher control and disturbance score is calculated and mapped onto a value that is used to color the student model.
- Surface Map Visualization: Similar to the radius and color visualization, difference value between two scores is mapped into a map on the classroom floor surface, integrated with the potential disturbance behavior influence effect of each student.

Figure 2.3: Radius and color visualization for classroom management(left) and the transparency map for eye tracking (right) (cf. [Har24])

Visualization of voice analysis

The Teach-R application was extended with a visualization feature for voice analysis (cf. [Rec25]). In the study, two visualizations were implemented to represent voice volume (see Figure 2.4 and 2.5). The first is a circular visualization, where a colored sprite (blue at the center, red at the edge) scales according to the user's speaking volume and position. This provides a spatial indication of how loudly the teacher is speaking in the virtual classroom. The second visualization is a fog visualization, which uses Unity's built-in fog effect. The density of the fog increases or decreases relative to the speaker's volume, simulating the logarithmic behavior of decibels. This creates a surrounding atmosphere that changes dynamically with voice intensity. Further, the Teacher Clone is also provided for voice replay. The Teacher Clone in Teach-R is a simplified copy of the teacher model placed in the virtual classroom. It can interact physically, record and replay audio when touched, and provides a basic tool for teachers to review and reflect on their communication during training. The study also includes a visualization page (Figure 2.6) in CoachVR that displays text content, waveforms, and basic text analysis.

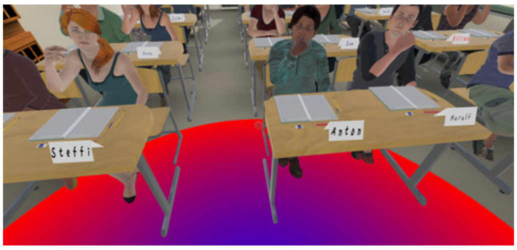

Figure 2.4: Circular Volume Visualization (cf. [Rec25])

Figure 2.5: Speech Fog Visualization (cf. [Rec25])

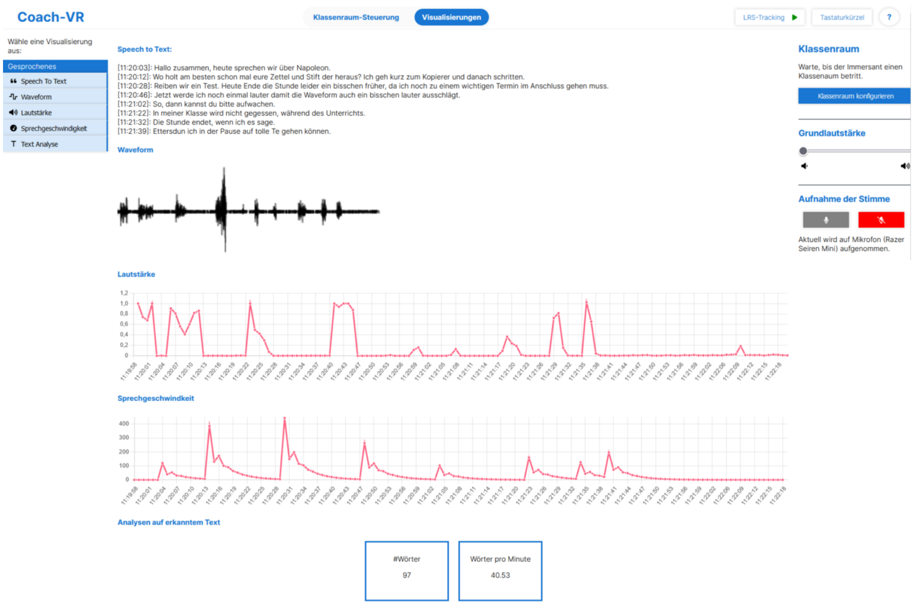

Figure 2.6: Voice Analysis Page in CoachVR (cf. [Rec25])

Teach-R has incorporated diverse visualization methods—such as heat maps, scatter plots, bar charts, color coding, surface maps, fog effects, and clones for replay. The presented visualizations have mainly focused on focused on behavioral and communicative aspects. The heart rate monitoring can extend as a physiological indicator of stress and classroom engagement.

Chapter 3 Conceptualization of Visualization

The goal is to provide heart rate visualization in Teach-R and post-session visualization feedback. Possible solutions and restrictions of visualizations will be presented here.

3.1 Visualization in Teach-R

3.1.1 Visualization Form

Heart rate is a physiological data in Teach-R

As introduced in **Section 2.7**, existing visualizations in Teach-R are in 3D and they focus on behavioral data. Heart rate, as a form of physiological measurement, is relatively difficult to externalize, especially within the classroom environment. As introduced in **Section 2.1 and Section 2.2**, some studies have still explored 3D heart rate visualization in VR. In these studies, variations in heart rate were used as a controlling factor that determined the content presented to users within the VR environment. By maintaining a specified heart rate, users could unlock or change scenes(cf. [DCL+24], [EGH+25], [HWO+25]), or experience additional special heart rate feedback such as changes in the glow intensity of firefly-like visual effects within the VR environment (cf. [CSV24]).

Limitations for visualization

However, most of these studies employed VR scenarios specifically designed for heart rate research, whereas in Teach-R we must consider whether such designs might conflict with its primary task of classroom management. For instance, visual distortions and frame rate alterations would significantly interfere with teachers' instructional activities, making them unsuitable for integration into Teach-R. Any NPCs or reward objects that appear in the classroom must also be contextually appropriate and pedagogically reasonable.

Therefore, as inspired by mentioned studies in **Section 2.2**, the design of visualizations can be considered from the following two perspectives.

Possible visualization method

One is the change of the classroom environment. The elements of the environment can be the overall color tone of the scene, the intensity of classroom lighting, and the weather or scenery outside the classroom windows can be used as mechanisms to convey heart rate feedback. We should always remember that during classroom activities, changes of the environment should not affect the teaching experience.

The other one is the visual overlay. We may slightly adjust the VR headset's field of view or directly use a GUI within the scene to display heart rate. However, it is also necessary to consider the impact of these settings on both immersion and contextual appropriateness in the classroom. As Hein commented in their study (cf. [HWO+25]), the design should allow users to “read” their body’s performance through in-world cues, not external metrics. They think this approach aligns with broader HCI work on embodied interaction and tangible computing, where the boundary between system and body becomes more fluid and perceptually integrated.

The heart rate range should be well-managed

But there is something we need to keep in mind about the change of environment visualization method. It is a common sense that heart rate variations are expected to be more moderate compared to the pronounced fluctuations typically observed in physical exercise or horror-based VR scenarios. Taking individual differences in heart rate into account, the effects of environmental changes may either go unnoticed or make it difficult to establish a reasonable mapping range. Therefore, visual overlay will be adopted as the primary approach for conveying heart rate feedback. Considering change of environment is a highly promising approach, the visual overlay will still incorporate heart rate zones, serving as a preparatory step for implementing environmental changes as feedback in the future.

The Smartwatch Implementation Idea

The next step is to consider how to implement the visual overlay, either by enforcing it directly in the VR headset’s view or by displaying it through an object within the classroom.

The initial plan of HR vislization

The initial idea of heart rate visualization is to reuse the visualization panel (as shown in Figure 3.1) and display the visual content. The menu now has a data visualization panel that integrates footstep tracking, positional data, and eye focus information. It can be accessed from a textbook object on the teacher’s desk in the classroom of Teach-R. For better visualization, it is essential to first resolve the problem of the presentation medium.

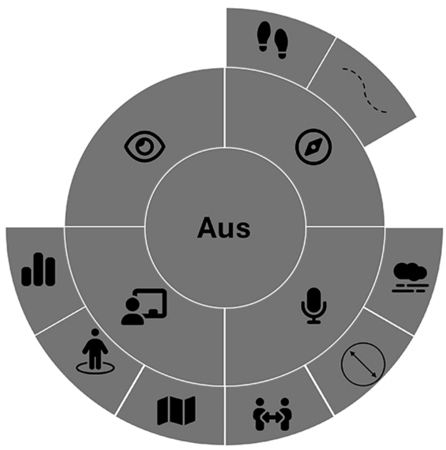

Figure 3.1: The current visualization page menu (cf. [Har24])

Choose a suitable modality for heart rate display

As the visualization of heart rate monitoring holds significant real-time value, limiting heart rate visualization to post-session presentation is regrettable. Given the immediacy of heart rate, we also want users to be able to see the heart rate display directly without having to intentionally open an object. At present, the visualization depends on opening a book object in the classroom. If the heart rate display has to be accessed through this point, it means that whenever users want to check their heart rate, they need to walk to the textbook and open the visualization interface, or keep the heart rate display mode turned on all the time. Hence, if we intend to visualize heart rate changes in real time, determining a suitable medium for presentation poses a significant challenge.

Direct display in the view in not immersive

We also considered whether the heart rate could be directly displayed in numerical form within the VR view. However, this idea was soon dismissed, as mentioned in **Section 2.1**, the sensation of "being there" is a key aspect of the VR (cf. [Bai18]). Directly displaying heart rate in the VR view is not consistent with real-world logic. Introducing elements that feel unnatural could disrupt the VR experience. One possible alternative is to display the heart rate in the view only when there are significant changes. However, this would still inevitably interfere with the VR scene, and determining the appropriate timing for such displays would also require careful design. Moreover, such forced displays might distract trainees and potentially increase their anxiety.

The smartwatch is an optimal method

Thanks to Grioui's study (cf. [GB23]), their work on heart rate visualization through virtual smartwatches has provided us with significant inspiration. Displaying visualized data through a virtual smartwatch proves to be a suitable method. Firstly, it preserves the trainee's immersion in the VR environment, as a virtual smartwatch is not unnatural. Secondly, it can reduce psychological discomfort, as the heart rate is not constantly imposed upon their view. Moreover, according to [Bla21], when people look at the data during the course of an activity, usually they consume the information in short time-lapses (individual glances of 5 seconds or less). This allows us to deliver a visualization with higher information density in a virtual smartwatch.

3.1.2 Visualization Decisions on Smart Watches

Various methods exist for visualizing heart rate. The most common way to present heart rate is through line charts. Depending on the specific context or scenario, other methods are also used.

Challenges in the smartwatch visualization

The challenge is to design the visualization on the smartwatch. In Figure 3.2, there are some example ideas of 2D heart rate visualization. However, the design process must first consider the visual quality of the visualization on a small smartwatch in VR environment, and secondly, the density of information conveyed to ensure clarity without overwhelming the trainee. To achieve the second goal, we also have to consider two aspects. First, the raw data from the device is quite basic and may have latency, which can hinder the accuracy of visualization and lead to misinterpretation (cf. [GB23]). Secondly, [AHBI17] emphasized the importance of having a combination of data types to improve clarity and readability. Therefore, when designing visualizations, we should follow these principles:

- 1.Use commonly accepted and standardized formats to facilitate quick responses from trainees.
- 2.Use a clear format that is easy to read on a small device such as a smartwatch.
- 3.Present historical data rather than isolated values to avoid delays or misinterpretation.
- 4.Combine multiple visualization methods to support accurate interpretation.

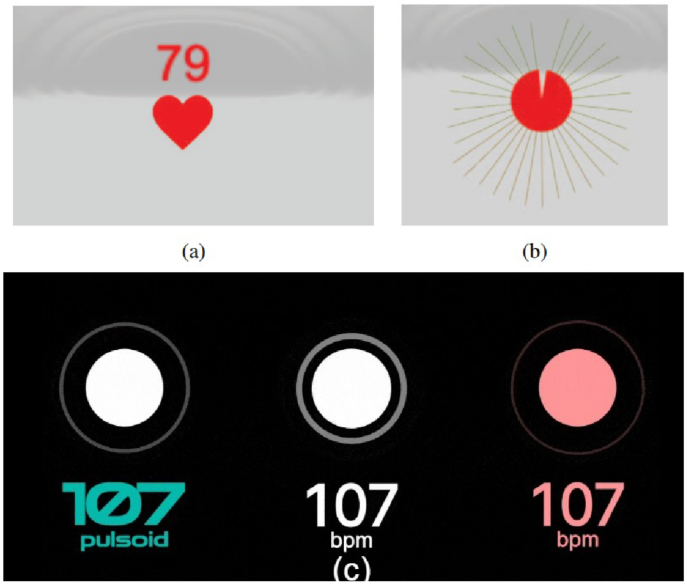

Figure 3.2: Examples of Different Heart Rate Visualization: (a) A simple icon with a changing number (cf. [GWZE18]) (b) A circular graph : The density of the surrounding lines indicates how fast the heart rate is (cf. [GWZE18]) (c) An animated visualization combining a changing number with dynamic circular and ring elements (from pulsoid.net).

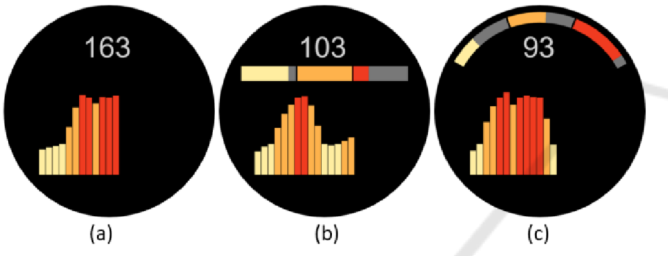

Figure 3.3: Three Different Bar Charts with(without) HR Zone (cf. [GB23])

In summary, and based on (cf. [GB23]) and as shown in Figure 3.3, the bar chart is a suitable option. Bar charts have the privilege of visually encoding the heart rate value by bar length and the heart rate zones by bar color simultaneously. The length of each bar depicts the HR value per unit time, and the color of each bar can indicate which HR range it belongs to. If we add historical data (summary bar at the top), one can easily quantify proportionally and estimate the time spent in each HR range.

3.2 Visualization in CoachVR

In CoachVR's visualization, the heart rate for the entire session is visible, but we also aim to integrate heart rate with classroom management. Therefore, student behaviors should also be included, allowing users to observe what was happening in the classroom at the same time.

Keep an overview of Student Behaviors

Both heart rate and student activities should be presented intuitively together, allowing users to review any given time period with ease. Fortunately, student behaviors and heart rate can both be represented as time-series data. It is possible to present these two types of data in parallel within a single view. An easy solution is to provide the current status of all students in a floating window at any selected point on the heart rate chart. However, this method is not sufficiently intuitive, because the overall information on student activities is hidden, it is difficult for users to form a general understanding of student behaviors throughout the entire session.

Two possible approaches

The other two possible visualization approaches can be considered. The first is a parallel timeline view. Heart rate and student behavior events are overlaid along the same time axis, enabling users to observe their relationship at a glance. This approach has the advantage of being intuitive and providing a holistic overview of the entire session, but it may become visually cluttered when the amount of data is large. The second is an event-aligned visualization. Student behavior events serve as anchor points and heart rate changes before/during/after these events can be examined. While this method supports a more detailed analysis of the physiological responses associated with specific classroom dynamics, it provides less immediate visibility of the session as a whole.

Since preserving a holistic perspective of both student behaviors and heart rate was essential, we opted for the parallel timeline view approach, despite the fact that it inevitably introduces some visual clutter in the visualization. This clutter can be alleviated through techniques such as zooming into particular time segments or presenting more information via floating windows.

Spatial Memory

In addition to providing an overall impression of the entire session over time, we also want to provide some impressions in terms of space. In Teach-R, teacher trainees can see the students' names, and as described in **Section 2.7**, the classroom seating plan also differ. Therefore, teachers have a spatial memory of the entire session, and if the corresponding student seating information could be displayed alongside the heart rate statistics, it would help teachers with recall and self-assessment. The seating plan can be visualized using a scatter plot, with each point representing a student and color coding used to indicate corresponding student behaviors. In the seating chart, we want to show what behaviors each student engaged in throughout the entire time period. With the availability of these two views, teacher trainees are able to reconstruct the session along both temporal and spatial dimensions.

Choices of Charts

The next issue concerns the choice of visualization method. Generally, as a form of time-series data, heart rate can be represented using line charts, scatter plots, or bar charts. To maintain visual continuity, line charts and bar charts are the two primary options. However, because heart rate is collected at a high frequency, bar charts would require rendering a large number of bars. For the sake of both performance and simplicity, the line chart is therefore the preferred option.

Integration of Seating Plan

The remaining challenge is how to integrate the seating plan into the visualization. The two time-series datasets already generate a considerable amount of information, and adding the seating plan on top of this would make the visualization even more cluttered. Therefore, we considered presenting the seating plan as a separate view, which can be integrated into the visualization as a switchable option.

3.3 Color Scheme of the Visualization

Choices of color

The goal is to create a colorblind-accessible visualization with clearly distinguishable colors even on a small smartwatch screen. People with color blindness can perceive a wide range of colors, but certain color combinations are difficult for them to distinguish. According to Okabe (cf. [OI16]), following are two simple principles of Color Universal Design.

- 1.Choose color schemes that can be easily identified by people with all types of color vision, in consideration with the actual lighting conditions and usage environment.
- 2.Use not only different colors but also a combination of different shapes, positions, line types and coloring patterns, to ensure that information is conveyed to all users including those who cannot distinguish differences in color.

Okabe (cf. [OI16]) recommended color combinations of 3–4 colors.

- 1. Color Universal Design (CUD) Recommended Set (3 colors): Blue: 0072B2, Orange:E69F00, Green: 009E73
- 2. CUD Extended Set (4 colors): Blue: 56B4E9, Orange: E69F00, Bluish Green: 009E73, Yellow: F0E442

These colors are from the Color Universal Design (CUD) guidelines developed by Masataka Okabe and Kei Ito, which are widely cited in scientific and academic visualization and are scientifically tested to remain distinguishable under all major types of color blindness. The color design mentioned here is used in Teach-R, while the color design in CoachVR is consistent with the color scheme of student behavior.

Chapter 4 Implementation

4.1 Implementation in Teach-R

The role of Teach-R in the simulation session

Teach-R serves as both the simulation host for classroom activities and the provider for real-time heart rate visualization and data transmission services.

4.1.1 Preparation Work

To implement the Learning Analytics functionality effectively, we need to introduce several key dependencies.

- Follow OmiLAXR the set-up instructions and use tools provided to edit xAPI definition in the project
- Include *LRSFetcher* prefab and scripts to query and fetch from Learning Record Store
- Include *StudentTrackingBehaviour.cs* and *StudentTrackingComposer* from *eye-track-development* branch to record the activities of virtual students.

4.1.2 The SmartWatch in Unity

All heart rate visualizations are rendered directly on the smartwatch. The goal of the smartwatch is to present real-time heart rate data to Teach-R users in a way that remains calm and unobtrusive—providing useful feedback without demanding excessive attention.

The guiding principle: independent module design

One guiding principle is the independence of individual modules. Thanks to the OmiLAXR pipeline, the heart rate data provider is designed to be independent, meaning that we can switch to any other theoretically feasible method for heart-rate transmission with minimal modifications.

With this foundational architecture in place, the *Heart Rate Manager* enables us to effortlessly adjust heart rate display and transmission parameters—such as update frequency.

All functionalities are encapsulated within a single prefab. Activating the instantiation controller is all that's needed to enable the smartwatch feature. This design allows us to start or stop the functionality at any time within the project with ease.

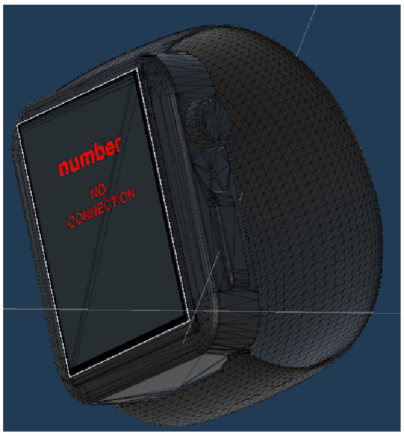

Figure 4.1: The smartwatch prefab

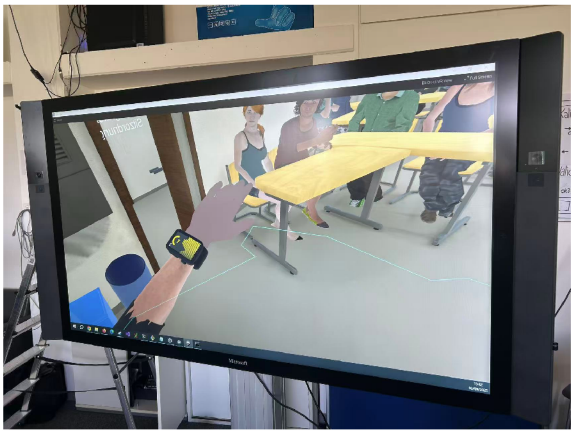

Figure 4.2: The smartwatch visualization in Teach-R

4.1.3 The Model of the Smartwatch

How did we build the 3D model of the smartwatch

The body of the smartwatch model can be downloaded from free model resource library CadNav[1]. In order to better adapt the smartwatch for Teach-R (mainly a larger screen ratio), TinkerCAD was used to modify a simpler ring-shaped wristband. Unity allows users to directly import the *.obj* model designed in TinkerCAD. The model consists of two large components-watch body and wristband. After that, all we need is to create a suitable material and apply the material the watch model.

The logic components of the smartwatch in the Unity project

The code logic attached to the smartwatch body is structured into two primary parts: one responsible for its appearance and visual feedback, and the other handling data management and transmission.

4.1.4 Visualization logic in Unity

In the first part of the system, two Canvas UI elements are placed on the smartwatch to display: a primary canvas serving as the main screen interface, and a secondary canvas overlay used specifically for heart rate visualization. This layered setup enables switching or extension to additional functionalities by simply toggling or replacing the overlay canvas.

The color setting of the visualization

The visualization functionality is primarily implemented in *SmartWatchScreen.cs* and *SegmentGaugeChart.cs*. First, it's important to note that the bar chart reflects heart rate through both color and height. There are three colors—blue, yellow, and red—corresponding to increasing heart rate levels, from low to high. The same color coding scheme also applies to the numeric heart rate reading above the bar chart.

The description of the numeric reading and the bar chart

The *SmartWatchScreen.cs* serves as the main role in the visualization. It accepts inputs as the number of historical heart rate data (*maxVisibleValueAmount*) that can be observed directly—displayed as a bar chart. The visualization is implemented using a queue of heart rate data. The bar chart is redrawn based on the data currently stored in that queue. The color and height of all visible bar elements are defined individually according to heart rate data they represent. *gameObjectList* stores these

[1] See *The smartwatch model* at `https://www.cadnav.com/3d-models/model-51564.html`.

bar element game objects and waits to be redrawn upon new arrival of heart rate data.
Sometimes rapid changes in the numeric heart rate reading can look visually abrupt, so we use a coroutine to fade the number out. The basic principle is to use a delta time to gradually change the alpha value.
If heart rate data transmission has not started or the connection is interrupted, the smartwatch will activate a 'connection lost' panel instead of only displaying an awkward zero reading.

The description of Gauge chart script

Simultaneously, the *Segment Gauge Chart* records all historical heart rate data and aggregates it, displaying the proportions of each heart rate range in the segment gauge chart. The chart consists of three overlapping ring images, layered in the order of low-, mid-, and high- heart rate zones. It computes the proportional fill for each heart rate segment and apply it to its corresponding ring. To create smooth transitions between states, *Mathf.Lerp* is a good option, which yields significantly better visual effects.
The last minor feature is displaying a system clock, formatted as hh:mm.

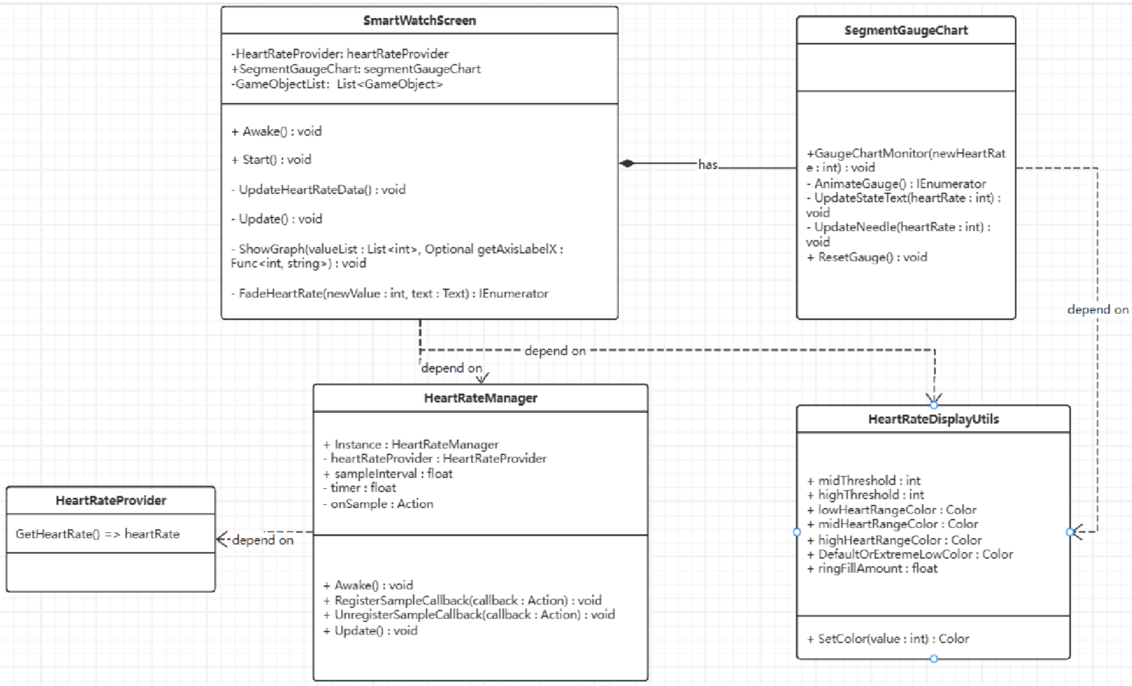

Figure 4.3: The UML Diagram of smartwatch visualization logic

4.1.5 Data Management logic in Unity

In the second part, the system comprises four functional modules:

- LA – A pipeline from OmiLAXR records the necessary activities.
- Student Seat Normalization – It normalizes initial positions of students and teachers at scene setup and transmits them to CoachVR.
- Heart Rate Manager – This module adjusts heart rate display frequency to meet various requirements.

- Statement Manager – After querying the Learning Record Store (LRS), it collects and sends the required data to CoachVR.

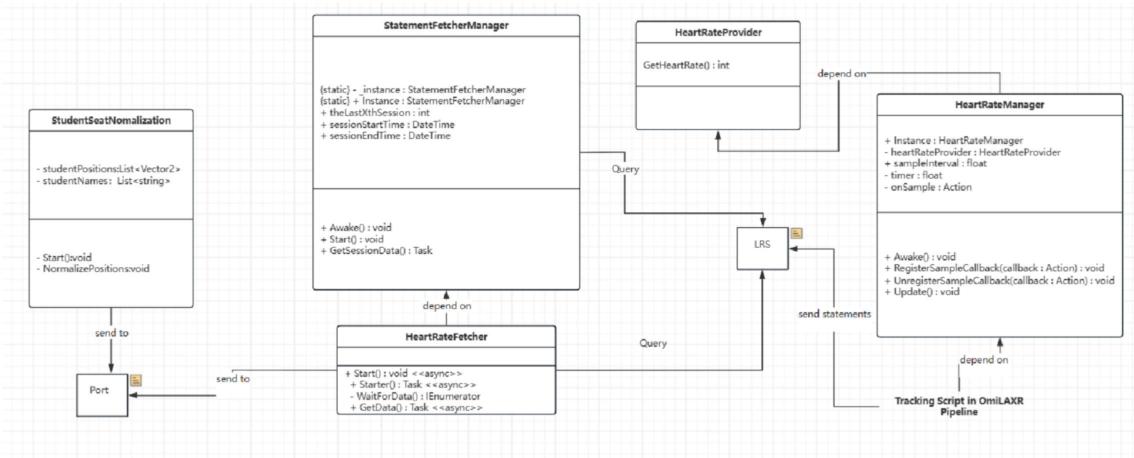

Figure 4.4: The UML Diagram of Data Transmission Relevant Class

Detailed Explanation of the four components

The *LA* game object is directly from OmiLAXR packages. Four scripts are added to the pipeline to track and compose heart rate data and student behaviours. To get real-time heart rate data, a *Heart Rate Provider* has to be attached to the pipeline to provide heart rate data. Additionally, it also returns time-out messages for connection lost status. Ensure the correct API key and session details are filled in.

During scene initialization, positions of students and teachers are normalized and sent by *CoachRtc* to CoachVR in *Student Seat Normalization* so that we can render a seating chart in CoachVR. Teachers' initial positions are also included in this calculation, and will likewise appear in the rendered diagram. The normalization scale can be adjusted. To better fit the graphical visualization in CoachVR, the scale is typically set below 0.8.

The *Heart Rate Manager* is currently designed to manage the update frequency of the heart rate. Another task is to reflect on changes of *heartRate* in *Heart Rate Provider*, so that visualization and statement pipeline can notice the update. Since heart rate sensors typically produce data at a much higher rate than needed in our experimental setup, it limits the heart rate updates to once per second at most.

The *Statement Manager* is responsible for querying from LRS and transmitting xAPI statements to CoachVR. Although we store all heart-rate data in the LRS in real time, the latest *React.js* version of CoachVR doesn't currently support consistent live connections. As a result, data from the current session won't appear in CoachVR until the session has ended. In essence, CoachVR only displays true post-session data.

Each time we query the LRS, we first retrieve the visible session information. Then, based on the session order (sorted from newest to oldest), we query the LRS again to obtain data for the targeted session.

Therefore, during the current session, the system defaults to displaying data from the previous session. If we would like to view data from an even earlier session, we can enter the corresponding number in the Inspector's 'The last x-th session' field (default is 0). If we want to review data from the current session, the best approach is to stop the session, halt new xAPI statement transmission, and then restart Teach-R.

4.1.6 Sending wrapped packets

To achieve this, the package *TeachR.RTC* must be included.
To send a data packet to the port, we need to package the data in JSON and include a header. Since sending packages is quick and simple, each data module handles its own transmission in its respective script.
Each script first collects and stores data in its corresponding container, then serializes the data and sends it to the specified port at one time. The entire query-and-transmission process usually completes within 5 seconds.

4.1.7 The Instantiation of the Smartwatch

The smartwatch instantiation is implemented in *SmartWatchInstantiationController.cs*. One feature in this script is to ensure that the smartwatch is correctly attached to the teacher's *Left Hand* game object.
In Teach-R, the hand and forearm are separate—disconnected at the wrist. Since the watch needs to sit on the wrist, we had to decide whether to attach it to the arm or the hand. Ultimately, we chose to attach it to the *Left Hand*, because it will be easier to rotate the hand to look at the watch, even though this may cause some mesh clipping at certain angles.
To ensure correct positioning and rotation, at first manually adjusted the smartwatch's position and orientation during runtime until it aligns properly on the teacher's *Left Hand*. Then record values (Transform and Rotation) from the Inspector and input them into the instantiation script. This ensures the watch consistently fits correctly across different scenes.
To maintain low coupling and high cohesion across modules, we write this prefab-based instantiation controller so the smartwatch can be shown or hidden as needed.

4.1.8 The challenges

The challenges in Unity

Numerous challenges arose during the implementation. In Unity, most of the issues we encountered were related to compilation management and the Unity life cycle. Incorrect script compilation order or life cycle misuse can prevent the project from running correctly or lead to errors. Since we need to control the heart-rate update frequency, we implement a Timer to calculate the time elapsed since the last update. When we initially implemented the Timer, it didn't work at all. After a long time of investigation and searching, it occurred that the issue likely stemmed from integrating the OmiLAXR pipeline and introducing coroutines, which caused the Timer to fail.
Another challenge is Unity versioning. Different Unity versions break some OmiLAXR-related dependencies, forcing me to either comment out code or tweak version check branches manually.
Using Unity's UI components, such as TextMeshPro, would cause the entire screen to freeze. At the time, we could not identify what was triggering the problem and had to manually check each GameObject one by one to locate the offending UI component. Replacing it with a simpler Text component resolved the issue—but the mechanism behind the bug remains to be explored.

The challenges in Unity-CoachVR Framework

The biggest challenge is the transmission from Unity server end to React front end. The new CoachVR version is not stable enough. Starting the React front end first may accidentally occupy the port, preventing correct data transfer. If a similar issue occurs, manually terminate the process listening on that port via the command line. After starting the project, the *PreviewRoom* scene is not automatically added to the scene hierarchy in the lab's build environment. We must manually locate and add this scene in the scene view, otherwise the teacher's position cannot be loaded properly, preventing a valid session from starting.

4.2 Data Visualization in CoachVR

The previous version of CoachVR was built using an *Angular* architecture. In the new version, CoachVR will be implemented with *React.js*. *React.js* is more like a library, not a fully framework, it is more flexible and has incremental adoption.
As introduced before, CoachVR controls student behaviour and other classroom setting. It also serves as the primary tool for post-session visualization and evaluation.

4.2.1 Introduction to the Visualization Package

ApexCharts is an open source project licensed and it is free to use in commercial applications.It provides extensive capabilities and is user-friendly. Various types of charts such as line, bar, area, donut, pie, and more are provided in this package. Modern UI style allows users to create responsive charts and dashboards.
React-ApexCharts is a wrapper component for ApexCharts ready to be integrated into the *react.js* application to create stunning React Charts [2]. To work with *React-ApexCharts*, the package *react-apexCharts* must be included.

4.2.2 The Structure of CoachVR Visualization

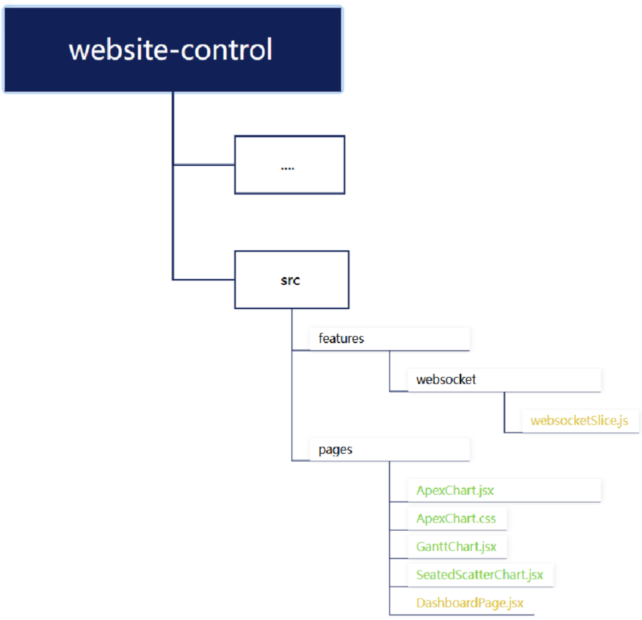

Figure 4.5: The Structure of new CoachVR: New Scripts are Green. Modified Scripts are Yellow.

[2] See *ApexCharts* at `https://apexcharts.com/docs/react-charts/`.

4.2.3 The functions in the visualization

Graph Type:

- A time series heart rate line chart.
- A gantt chart showing all recorded students behaviours information(type, duration)
- A classroom seat graph showing how many continuous durations of bad/medium/good behaviours are recorded in the whole session.

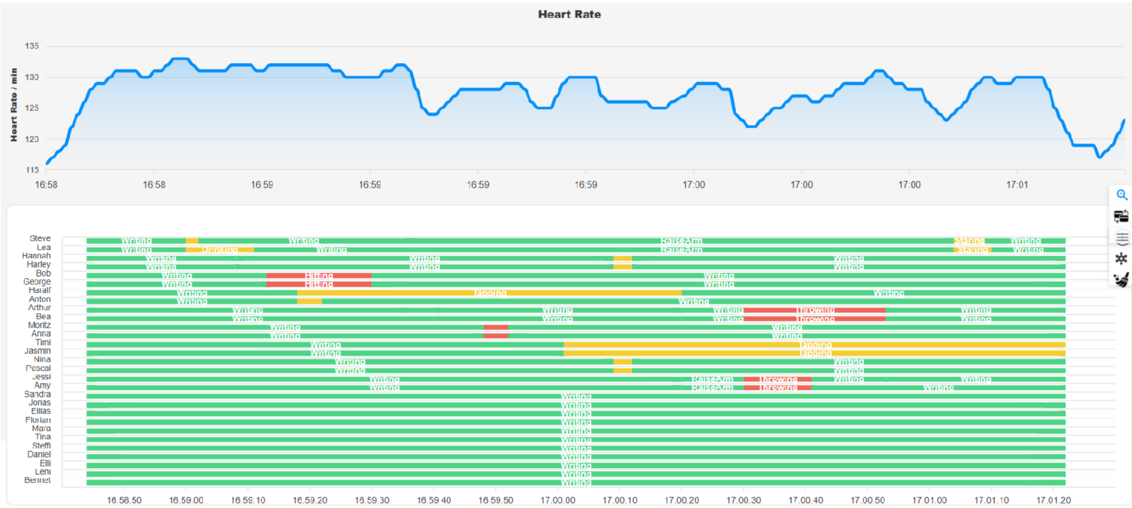

Figure 4.6: Heart rate line chart (top) and Gantt chart of student behavior (bottom)

Figure 4.7: Heart rate line chart (top) and seat chart of student seating plan (bottom)

Functions offered in visualization:

- Line Chart: Zoom in/out to focus on wanted intervals: buttons in the toolbar OR directly hold mouse left-click to select.

- Gantt Chart: Highlight Activity: Click on bars. Click again to cancel.
- Classroom Seat Graph: Highlight Activity: For any student, click on small squares to show all activities of that kind. Click again to cancel.
- Additionally:

  1. A floating toolbar for buttons: a. Switch graph b. Clear highlights c. Freeze data: For the sake of convenience of focusing on a specific interval while having a good general overview in line graph, enable this to avoid synchronizing data in Gantt/Seat when Zoom in/out

  2. Hover windows for detailed information are always enabled in all graphs.

  3. Shared time axis for all graphs. Shown data are always consistent in 3 graphs unless the Freeze button is pressed.

4.2.4 Packet Reception and Data Process

Where Packet Reception happens

Packet reception is handled in *websocketSlice.js*, after which the different data is stored in React's DOM. When using the data, the scripts read it from React state, access the DOM via refs only when we truly need imperative reads (e.g., uncontrolled inputs or direct DOM manipulation).

The mechanism of Apexcharts

ApexCharts re-renders primarily on React state/props updates. When users change series or options, the chart automatically updates.
The series changes or option changes are mainly activated by users' Zoom-in/Zoom-out operation in *ApexChart.jsx*. When the user zooms the timeline (x-axis in line chart) in or out, the heart rate line chart updates accordingly, which is achieved by filtering the heart rate data within the effective view range in the line chart.

Shared Effective Range for all 3 graphs

Simultaneously, the effective view range is shared with the other two charts. They will also redraw their visualizations according to the effective data range.

4.2.5 Highlight Areas in the Line Chart

The time axes of the line chart and the Gantt/Seat chart aren't perfectly aligned visually. To better locate a student's behaviour on the line chart, a highlight area function is introduced to mark the corresponding behaviour interval.
When users click on any activities shown in Gantt Chart or any squares which represent students with active records in Seat Graph, the corresponding areas in Line Chart will be highlighted. Highlighted areas are tracked by using student activity information to prevent highlighting the same activity multiple times. If the same student activity already exists, it will be removed and toggle off the highlight when the same activity is clicked again. Both Gantt Chart and Seat Graph employ the same strategy.

4.2.6 Freeze Effective Range in Gantt Chart/Seat Chart

The line chart and the other two charts always change in synchronization. If the user wants to maintain the current view of student activity, while also wanting to examine how heart rate activity is distributed across that time range in the line chart, a separate feature must be designed to prevent the data from being redrawn.

Based on this feature, we introduce the concept of an ‘Effective Range’, which represents the currently displayed time interval and is used to filter the relevant data. By default, the Effective Range for all visualizations is synchronized with the time-axis range of the line chart. When the user wishes to maintain a fixed view of student activity for a specific time interval, the Effective Range is locked to the current time-axis range of the line chart. Simultaneously, the user remains free to zoom the line chart in or out.

At the same time, a notification pops up in the upper-right corner of CoachVR, informing users of the start and end of the frozen time range they’ve selected. Until the user clicks the feature again, all visualizations immediately synchronize again and return to their default state.

4.2.7 Floating Toolbar and Hover Windows

The configuration details for the *Floating Toolbar* and *Hover Windows* are implemented in ApexChart.css.

The reason for floating toolbar

To facilitate triggering certain global functions within the visualization, user interaction buttons are required. To ensure these buttons remain visible and fixed in an appropriate location, a *Floating Toolbar* is used. It is anchored in the vertical center of the right side of the view.

What is Displayed in Hover Windows

To reveal more detailed of activity information without cluttering the visual interface, *Hover Windows* feature is applied across all visualizations. When the user hovers the mouse cursor over a visual element or button, a temporary window appears displaying additional information about that element or button. In the line chart, the information shown indicates the precise moment when heart rate was recorded. In the Gantt Chart, the windows display the precise start and end times of the student’s activity, as well as the activity type. In the Seat Chart, the windows display the number of student activities of the specified type that occur within the current Effective Range. Hovering over a button triggers a tooltip that displays the name of the button as a hint.

4.2.8 The Color Scheme

Focus on the color scheme of student activity

Because everyone’s heart rate range varies and the line chart primarily illustrates trends rather than absolute values, it’s difficult to assign a fixed color scale based on absolute heart rate ranges. Therefore, no color scheme is configured for heart rate plotting. Instead, color schemes focus on student activity types.

Origin of the color scheme

In the earlier version of CoachVR, there are three main types of student behaviour: Good, Lightly Bad, and Bad, which are color-coded green, orange, and red, respectively. To ensure consistency, the visualization in new version of CoachVR retains the same color scheme.

The reflection of the consistency of the color scheme

Color scheme consistency is maintained across the visualizations: in the Gantt chart, the student behaviour bars use the same colors. In the Seat Chart, the four squares representing student behavior types also retain these colors. In the Hover Window, the text detailing information is displayed in the same color scheme.

4.2.9 The Challenges

As mentioned earlier, the first challenge is how to correctly receive and process the Packet.
The greatest challenge is understanding and effectively utilizing React's DOM mechanism.
A notable challenge lies in configuring the placement of UI components: designers have to manually input layout parameters and continuously fine-tune them. Fortunately, React's dynamic update capabilities mean that changes appear instantly without requiring a full page reload.
Another issue related to data labels on the time axis. High-density time data can cause labels to overlap or display in an unreadable manner.
Another often overlooked challenge concerns time zones. The LRS records timestamps using UTC, but the CoachVR visualizations must display them in the user's local time zone. If proper conversion isn't applied, session data will be displayed incorrectly.

Chapter 5 Evaluation

The purpose of the user study is to gather participants' feedback on the visualization design, uncover any design bugs, and collect insights for future work. Totally 9 participants took part in the user survey. Participants immersed themselves in the Teach-R and engaged with the visualizations within CoachVR.

5.1 Evaluation Design

This section primarily describes the details of the user study, including the composition of participants, the user study process, and the design of the questionnaire. The user study was voluntary and unpaid. Vitamin water was provided during the user study sessions, and snacks were given at the end as a token of appreciation. Invitation to participate in user research was sent first, including details of the study location. Appointment schedules were collected by a calendar tool. LTI Lab usage was requested at last.

5.1.1 The Composition of Participants

Demography information of participants

The participants were primarily eight friends and acquaintances, consisting of undergraduate and graduate students from RWTH Aachen University, and one additional special participant was an employee/PhD student of the chair LufgI9.

Among the nine participants, three of them were female, and six of them were male, with ages concentrated between 25 and 30. Three of them were undergraduates, and five were master's students, one was from the chair LufgI9 and she was very familiar with Teach-R and CoachVR framework. Almost all participants were studying or used to study in STEM fields such as Computer Science, Electrical Engineering, and Mechanical Engineering, while one participant was studying Economics.

All participants possessed a university educational background and were generally familiar with operating computer equipment. The concept of VR was not unfamiliar to any participant. Two participants even regularly used VR for work purposes, while two others had used it for entertainment.

To assess participants' understanding of the concept of Learning Analytics, participants were asked to rate their comprehension on a self-assessment scale ranging from 'Not At All' (–3) to 'Very Much' (+3). About half of the participants selected 'Not At All'(-3).

Learning analytics is not a well-known concept

The average score was –1.0. If not for one participant with professional expertise in the concept, this score would likely have been lower. The concept of learning analytics should have been less familiar among nonspecialist groups. The answer's median score was –2.0, and the overall variance was 4.2.

5.1.2 Procedure of the User Study

A full participant session lasted approximately 15 minutes. The study was mainly held in English and was conducted in the LTI lab of the LufgI9 chair, at the computer science center of the RWTH University Aachen.

Preparation Step

Participants were first instructed on how to correctly wear the VR helmet and how to properly use both controllers. Because the physical space was limited and natural walking could lead to collisions with obstacles, participants were also taught how to use the teleportation function. Next, participants were equipped with a heart rate sensor, and its functionality was confirmed. The purpose of measuring heart rate was deliberately not disclosed, in order to examine participants' understanding of heart rate recording.

Teach-R User Study Part

Once everything was set, the user research session officially began, with participants assuming the role of an invigilator to supervise the behavior of virtual students in a virtual exam. The VR session's end time was determined verbally by participants as they checked the time displayed on the VR smartwatch. The virtual exam ended after the specified duration of 3–4 minutes.

CoachVR User Study Part

Before the next step, Teach-R needed to restart in order to fetch the newest session data. After restarting, participants were invited to the Coach-VR visualization interface that showed their post-session heart rate data alongside the virtual students' behaviors, where they could directly view and interact with the line chart and the Gantt chart. Participants were allowed to freely explore to understand the visualizations. They then interact with the visualization interface to complete the pre-assigned tasks.

Questionnaire

The final step was completing the questionnaire, where participants provided basic demographic information, including age, gender, and educational background. They then answered questions about their previous VR usage and their understanding of Learning Analytics.

Participants completed the short version of the User Experience Questionnaire (UEQ-S), evaluating the smartwatch design in Teach-R and the visualization in CoachVR across several dimensions: usability, perspicuity, enjoyment, efficiency, and novelty. After rating each dimension, participants could provide feedback specific comments.

Minor Changes in the Study

During the user study, minor adjustments were made. The second participant was overwhelmed by the VR experience and consequently attended minimally to the heart rate watch, so the heart rate functionality was very subtle. To ensure subsequent participants noticed the real-time heart rate display, they were instructed to check the time themselves on the virtual smartwatch to end the virtual exam verbally. Another change was a bug in CoachVR visualization, after the first participant, to improve the visualization experience, the misalignment bug in *Gantt Chart* activity bars was fixed.

In the final four rounds of the study, four participants were invited to take part in a brief group discussion on the possibilities of improving the study design. Questions were asked to participants whether an additional or a different scenario description should be included in Teach-R session to required them to actually speak and attempt to teach a piece of knowledge they were already familiar with (in order to make the experience feel more serious). All four participants responded positively, suggesting that such a design might provoke genuine psychological reactions, as disruptive student behaviour could potentially affect their confidence, speech fluency and even heart rate.

5.2 User Study Result

5.2.1 UEQ Result

The study made use of the UES-S questionnaire and it focuses mainly on Pragmatic Quality and Hedonic Quality. Pragmatic Quality evaluates whether the system is practical and efficient. Hedonic Quality evaluates whether the system is interesting and enjoyable.

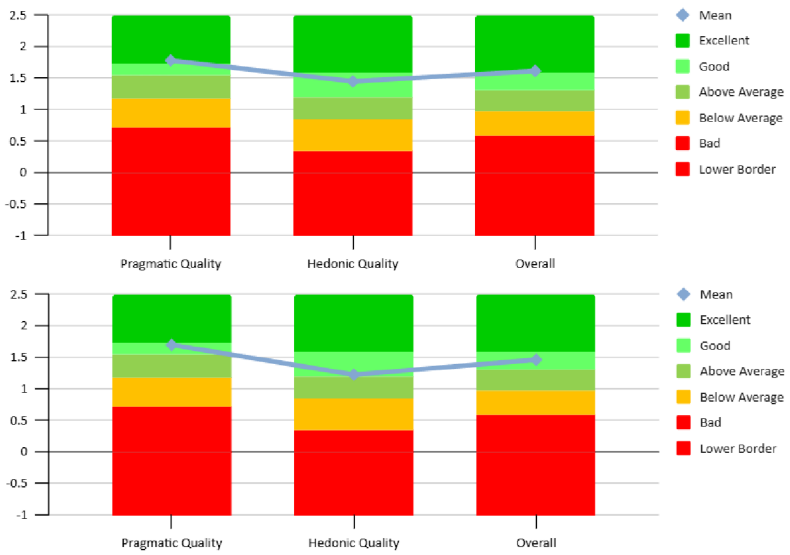

Figure 5.1: (a)The Upper Benchmark Graph: For Teach-R's Visualization (b) The Lower Benchmark Graph: For CoachVR's Visualization

Confidence intervals (p=0.05) per scale						
Scale	**Mean**	**Std. Dev.**	**N**	**Confidence**	**Confidence interval**	
Pragmatic Quality	1.778	1.162	9	0.759	1.018	2.537
Hedonic Quality	1.444	1.029	9	0.672	0.772	2.117
Overall	1.611	0.867	9	0.566	1.045	2.178

(a) Teach-R Smartwatch Visualization

Confidence intervals (p=0.05) per scale						
Scale	**Mean**	**Std. Dev.**	**N**	**Confidence**	**Confidence interval**	
Pragmatic Quality	1.694	0.788	9	0.515	1.179	2.210
Hedonic Quality	1.222	1.019	9	0.666	0.557	1.888
Overall	1.458	0.776	9	0.507	0.952	1.965

(b) CoachVR Dashboard Visualization

Figure 5.2: UEQ-S Analysis for Visualization in Teach-R and CoachVR

The UEQ-S Analysis for Teach-R's visualization

From the perspective of Teach-R's visualization, the results suggest that it achieved a moderate level of both pragmatic and hedonic quality. The higher mean score for pragmatic quality (1.778) compared with hedonic quality (1.444) suggests that the tool was recognized as more practical than enjoyable. However, the relatively wide confidence intervals indicate differences in individual responses, suggesting that user perceptions were not entirely consistent. Overall, the system demonstrated a generally positive evaluation.

The UEQ-S Analysis for CoachVR's visualization

From the perspective of CoachVR's visualization, the findings suggest that it was generally rated above average, particularly in pragmatic aspects (mean = 1.694). However, hedonic quality (mean = 1.222) was evaluated less positively, suggesting that the tool's capacity to offer enjoyable or engaging experiences was limited. The relatively broad confidence intervals again suggest differences across users, highlighting that perceptions of hedonic quality were less consistent. Overall, the visualization was considered practical.

A short Comparison

Both systems scored higher on pragmatic quality than on hedonic quality, suggesting that users consistently valued their usefulness more than the enjoyment. This indicates that while the tools effectively supported teaching tasks, they did not succeed in delivering engaging experiences. When comparing the two, Teach-R's visualization received slightly higher overall ratings (mean = 1.611) than CoachVR's visualization (mean = 1.458), suggesting some stronger perceptions of usefulness and satisfaction of the smartwatch. The hedonic quality score for CoachVR's visualization was noticeably lower. In summary, both systems were recognized as meaningful tools with positive contributions, but future improvements should focus on enhancing hedonic aspects to increase motivation and user engagement.

5.2.2 Open Questions

About the Project Design

Two users recommended using a wristband

Regarding the user study and the scene, participants had several suggestions. In the user study, one female participant noted that a chest-worn heart rate sensor felt somewhat inconvenient. Switching to a wrist-worn heart rate band might be a more convenient and natural option, and it would align with Teach-R's smartwatch feature in the real world. Another male participant also considered the wristband the better choice. One participant suggested making some of the students' bad behavior animations more subtle, as he felt that the task lacked challenge and he could identify them without needing to observe carefully, as the students' behaviors were very obvious to him and the distinction between good and bad behaviors was highly noticeable at the first sight.

Participants' Confusion during the User Study

To test whether the overall study design was intuitive, participants were told that they were acting as teachers, that they needed to time the exam themselves, and that they could view their real-time heart rate in the scene. As a result, one participant completely misunderstood the purpose of the watch. Another participant also misunderstood the act of checking the time on the watch to determine when to end the exam. He assumed the watch's primary function here was simply to tell time, and that heart rate was unimportant, so he suggested that a wall clock would be a better design.

The Visualization in Teach-R

First task: find heart rate visualization

First, participants were asked to find their heart rate in Teach-R in 30 seconds, and they began scanning the surroundings or examining the scene for a possible heart rate readout. Some participants successfully found their own heart rate. Without any hints, one participant successfully located the watch within 10 seconds (it should be noted that this participant may have accidentally seen the smartwatch model on the computer screen), while two participants saw the virtual watch as they looked down upon their own body. After being prompted, most participants raised their non-dominant hands, as they would in daily life. Still, a small number of participants kept looking for something resembling a large monitor.

the feedback: generally okay

The next question was about the intuitiveness of the visualization. The participants had no conceptual difficulty understanding what it was. They were then asked to start the virtual examination. Then they were told that they could observe their own heart rate during this period.

Presence of the smartwatch is insufficient

Unfortunately, most were absorbed in identifying student misbehavior, they did not actively check their own heart rate. One participant commented, the smartwatch was good for its flexibility, as it could be used when helpful and ignored when not. Those who had the capacity could take advantage of it, while for others it could stay out of the way.

Feedback part of the study

After the VR session, we asked the participants whether they understood the elements in the smartwatch visualizations. When asked about the semicircular gauge chart displayed above the heart rate reading, most participants either answered “no” or assumed it was only for aesthetic purposes.

At last, participants were asked about the idea and the design of the watch. Seven participants said the design was simple and helpful to their experience. One participant who was uncomfortable with the VR experience expressed a negative view of the smartwatch’s heart rate feature, as she raised issues with the VR device’s input sensitivity when teleporting and when raising her left hand to check the watch. One participant further commented that the design of the watch was unnecessary, as the heart rate in this virtual exam was not important.

Suggestions for the Visualization/Smartwatch in Teach-R

Participants were asked to provide suggestions for improving the smartwatch in all aspects.

For the visualization

Suggestions for the visualization

With respect to the heart rate display, concerns were raised that the bars occasionally extended too high and remained uncomfortably close to the numerical readout. Furthermore, the limited time span of the bar chart—restricted to under 30 seconds—was inadequate. Extending the display window was suggested as a means to facilitate the review of earlier heart rates and the recognition of emerging trends.

Some participants considered the standalone display of heart rate readings to be rather monotonous and suggested adding background icons or animations to make the visualization more engaging.

Suggestions for the smartwatch

For the Smartwatch

Regarding the smartwatch, a request was made for a timer feature to facilitate time-limited student tasks. At present, the watch displays only to the minute, so even in the virtual VR exam scenario of the user study, the timing function was not precise enough. Concerning the time display itself, feedback also noted that it was barely legible and should be made clearer in Teach-R.

One comment raised an interaction issue with the smartwatch. Not as the name suggests, the watch was merely smartwatch-styled and serves as a display. He would like more interactive operations to actively engage with it. He suggested that voice interaction or certain hand gestures could be a good interaction method for him.

The visualization in CoachVR

Task: The Meaning and Purpose of the initial Line-Gantt Visualization

First Reaction of Participants when Seeing the Initial Visualization

The initial visualization page showed the heart rate timeline for the entire VR session alongside the students' behaviour Gantt chart. Most participants reported that they understood what the visualization conveyed and its intent. The heart rate chart above and the students' behaviour Gantt chart below align on the whole session time axis. The initial visualization page was intuitive and simple, and one commented that the web interface was resonable designed and that finding the elements they wanted to examine was easy.

Two participants still did not understand the purpose of showing the heart rate chart alongside the students' behaviour Gantt chart at this stage, so they felt confused during both free exploration and the tasks.

Awareness of the Floating Toolbar

Task: Awareness of the Floating Toolbar

Exploration of the buttons in the floating toolbar on the right was almost entirely absent in the first minute. Participants only began trying to look for other features once the task of locating student seats was given. After some exploration, complaints arose that seat information was not visible in the *Hover Window*, leading to the assumption that the information was missing. The *Hover Window* of buttons in the *Floating Toolbar* was viewed by all after hints were given. During one free exploration, the *Seat Chart* visualization was opened, but its meaning was not recognized at the first sight.

Confusion in the Seat Chart

Task: The Comprehensibility of Seat Chart

In the *Seat Chart* view, repeated requests were made to confirm whether it represented a student seating plan. Due to Teach-R's settings, student names were not shown in the VR session. As a result, this was the first moment when attention really shifted to the student names in the whole user study, which greatly reduced the effectiveness of the *Seat Chart*. After seeing the names, participants were unable to connect them with the student activities they had observed during the VR session. At first, the display was assumed to show student behaviour at a specific moment. When this assumption proved wrong, it caused some difficulty in understanding. The most frequently asked question was what 'Active Records' in the *Hover Window* represents. Questions arose as to why positive behaviours appeared as multiple entries rather than a single one, and additional clarification was sought regarding the meaning of the last grey square in the four-square marker. The feature of clicking a student marker to highlight the student's behaviour was not intuitive, as their focus was concentrated on the interpretation of this visualization and most participants did not realize this feature.

Task: Switch from Gantt Chart to Seat Chart to Locate One Student

The next task was to identify a student behavior they were interested in, confirmed the student's name, and then located the target student's seat in the *Seat Chart*.

Switch between charts

It was generally recognized that the left side of the *Gantt Chart* displayed each student's name. In most cases, the target student's name was recalled, the visualization type was switched, and the student was then located in the *Seat Chart*. The feature of persistent displaying the target student's behavior range in the *Line Chart* was noted only once, and the participant facilitated a more efficient identification of the student's name in the *Seat Chart*.

Task: Comments on the Color Scheme

Overall, participants had no objections to the use of color of different student behavior types. The color scheme aligned with their intuitions about categorizing behavior types. Some participants were able to directly infer the positive or negative nature of the behavior through color differences.

Some participants felt that the color of the *Line Chart* was rather monotonous. Participants thought colors could be used to highlight the periods where heart rate fluctuated greatly, as they also mentioned this point in the previous task. The main flaw in the color scheme appeared in the *Seat Chart*, where participants could not understand the use of the gray squares.

The Zoom-in/Zoom-out in CoachVR Visualization

Zooming was the primary means by which participants changed the visualization content, and their usage of this operation is discussed separately here.

Task: Awareness of Timeline Alignment

Timeline Alignment Awareness

When the timeline was adjusted by zooming in or out, the corresponding changes in the students' behavior *Gantt Chart* below were noticed, and it was understood that the *Gantt Chart* was time-aligned with the *Line Chart*.

Task: Awareness of the Existence of Highlight Area Function

Test Result of Highlight Area Feature

After zooming into a specific time interval, the content of interest was examined. The *Hover Window* feature was consistently noticed in the visualization, briefly reviewed, and its information was quickly understood. In roughly half of the cases, after consulting the window, elements in the line chart and the *Gantt Chart* were actively clicked to test the interaction. Through this process, the *Highlight Area* feature was independently discovered. Additionally, most participants attempted to click the same Gantt bar multiple times. They felt that canceling with a second click was reasonable and intuitive.

Feedback noted that the *Highlight Area* was useful, but when multiple student activities occurred, the overlapping highlights became difficult to view.

The Freeze Function

Task: The Comprehensibility of the Freeze Data Function

All participants found the *Freeze Data* feature unusually difficult to understand. Some accidentally enabled it and became confused when the view stopped updating. Although there is a notice in the top-right indicating that *Freeze Data* feature is active, it was easy to overlook. Even after reading the notice, some participants still did not grasp its intended purpose. Participants would like more guidance for this feature or a button name change that makes it more intuitive.

Suggestions for the CoachVR visualization

General Suggestion for the Visualization Page

More Guidance

Participants mainly provided feedback on usage guidance and information density. More feature prompts rather than relying on UI interaction experience was mentioned to interpret the visualization. They were also asking for tooltip guidance to help them perform interactions. It was also suggested that adding names and descriptions to the visualizations would make them easier to understand and operate. In particular, they strongly recommended adding more guidance for the *Seat Chart* and the *Floating Toolbar*. Otherwise, they could not properly understand the purpose.

Improvements on the Line Chart

Suggestions for the Line Chart

A suggestion involved color-coding time intervals with large heart rate fluctuations. A particularly thought-provoking idea emerged during free exploration: by freely moving the cursor, the mouse wheel can actually control both the position and the extent of the timeline zoom with high precision. Building on this discovery, it was proposed that the *Freeze Data* feature be redesigned to follow the same interaction pattern as *Selection Zoom*, allowing users to actively select a target region and thereby gain a clearer understanding of the feature.

Improvements on the Gantt Chart

Suggestions for the Gantt Chart

The *Gantt Chart* received the fewest criticisms. Participants felt that the top and bottom charts are sometimes not perfectly aligned, which creates a slight visual distortion. They also noted a small rendering delay in the *Gantt Chart*. Although it did not affect usability, it would be better to hide the brief re-rendering process to provide a smoother experience.

Improvements on the Seat Chart

Suggestions for the Seat Chart

As noted in the previous section, student names did not appear in the VR session. In the correct version of Teach-R, students' names are supposed to be visible on their respective desks. As a result, participants found it difficult to use the names as cues to recall their student-management experience from the VR session. Nevertheless, they suggested adding the counts of successful interventions and timely responses to students' hand-raises, so that they could see whether they addressed student behaviors promptly. A suggestion was made to enlarge the student markers in the *Seat Chart*, as the current seating layout appeared somewhat cramped.

Highly Valuable Suggestions for Seat Chart

A request was made for the *Seat Chart* to support locating student activities at a specific moment. Another suggestion was more creative: incorporating an automatic playback system into the *Seat Chart*, enabling viewing, pausing at will, and freely inspecting student behavior at any chosen timestamp.

Suggestions for Hover Windows

Regarding the *Hover Windows*, it was suggested that in the *Line Chart* it should display key student behavior at specific time points, making it easier to connect behaviours with heart rate fluctuations. There was also a suggestion that the window information in the *Gantt Chart* be arranged in the form of “Student Name:; Student Behavior:; From:; To:;”.

Suggestions for UI Elements

A suggestion from a Computer Science background emphasized a preference for a UI with a navigation bar, along with customized features to filter and select target student behavior. Concerns were also raised about the button icons of the *Floating Toolbar*: the *Freeze Data* icon was mistaken for a settings icon, highlighting the need for more appropriate UI icon design.

5.3 Discussion of Limitation

5.3.1 Limitation of the Participant Composition

The primary objective of the user study was to evaluate the intuitiveness, usability, and comprehensibility of the visualization. Since most of the participants were invited from among friends or acquaintances, they tended to be cautious in providing feedback and were relatively conservative in offering critical suggestions. Therefore, the study has an inherent limitation in terms of participant selection. During the research process, we had to remind participants not to give “friendship points,” and encouraged them not to withhold negative feedback but instead to articulate any confusion they experienced. However, judging from the process, it was still difficult to prevent them from providing more positive evaluations than their actual perceptions.

Limitations in Participant Composition

From the perspective of participants’ social background, all of them had received higher education, and some were even specialized in computer science, making them quite familiar with computer devices and operations. This suggests that they were likely more adaptable to the simulated laboratory environment compared to the general population. Consequently, the diversity of participant selection could not be fully ensured in this study.

Lack of Participant Background Diversity

Among all participants, only one had much experience in teaching work, this participant also provided the only practical teaching-related suggestion in the study. Therefore, the feedback from the teaching community on this visualization tool was highly insufficient, making it difficult to capture the genuine instructional needs of practitioners.

5.3.2 Limitation of the Study Design Scenario

Possible Better Teach-R Session Study Design

In terms of the experimental setup of the Teach-R component, the scenario of acting as virtual exam invigilators was simple and easy to understand, but it was not very effective in fully engaging their minds and sustained attention. Most participants interacted with Teach-R in a rather mechanical way: They walked or teleported to a student to stop the behaviour and they then teleported back to the teacher desk, and soon they found the process monotonous. This indicates that the experimental scenario lacked sufficient immersion.

Minor Improvements in UEQ-S and Connection-Lost Feedback

As discussed in the previous subsection, due to the absence of student names in Teach-R, participants lacked a reliable reference point for recalling student behaviors, which made it difficult for them to describe the behaviors that left a strong impression.

5.3.3 Limitation of the Questionnaire Setting

Provide explanation in UEQ and improve questionnaires in time

Although the title of the UEQ-S specified that the object of evaluation was the visualization, one participant still overlooked this instruction and expressed uncertainty about whether they were evaluating the overall process experience or the visualization itself. This issue was discovered midway through the user study, making it impossible to determine whether earlier participants had correctly understood the evaluation target.

Regarding the UEQ-S, one set of word pairs (*conventional/Intentive*) created comprehension difficulties for participants. They had to consult a dictionary or ask for synonyms in order to grasp the concept. Therefore, when providing the UEQ questionnaire, explanations should be given for potentially uncommon terms.

5.3.4 Limitation of the User Study Exception Control

In the user study, one participant's heart rate sensor had poor contact, and the problem was only recognized at the end of the session, resulting in a heart rate graph that frequently displayed values of zero in an inverted U-shape. This indicates that relying solely on visualization feedback is insufficient to ensure proper sensor connection. A possible improvement would be to provide device-level feedback within Teach-R, such as controller vibration or other more appropriate cues. Alternatively, implementing a real-time activity visualization in CoachVR could also address this issue more effectively.

Little Perceived Presence of Heart Rate Visualization

One significant limitation in the user study was how to encourage participants to check their own heart rate. To achieve this goal, the first three participants were informed that they could observe their heart rate display within the session. However, they did not pay much attention to this piece of information. In the subsequent studies, participants were required to manage the examination time themselves. As a result, they frequently raised their left hand to check the time on the smartwatch, which also allowed them to observe their heart rate incidentally. However, participants' attention to the heart rate visualization still remained insufficient. For some participants, due to their limited impression of the feature, the heart rate visualization interface had to be shown again after the end of the VR session before they were able to provide useful feedback.

Little Perceived Presence of Color Scheme

Regarding the color scheme for different heart rate ranges in Teach-R visualization, the actual user study revealed that participants' heart rates remained relatively stable, so the readings and the bar chart visualization almost always appeared in the same color. As a result, participants rarely had the chance to observe the whole three color scheme. This also suggests that the Gauge Chart configuration was largely meaningless, as it will be a pure-color half ring chart. If the color scheme function is to be retained, the heart rate range color scheme should be anchored to a reference point based on actual initial heart rates of current users and should predict individualized low, medium, and high heart rate zones for different users.

Questionnaires should be modified

About the design of the smartwatch visualization, in the first several run-throughs, some participants provided feedback on the scale and height of the visualization. However, in the subsequent studies, the questionnaire did not include items addressing participants' preferences regarding the height of the bar chart or the amount of historical data to be displayed.

5.3.5 Burden of Cognitive Load to Check VR Session Data

Burden of Cognitive Load

In the visualization of CoachVR, there was a lack of user guidance and system-level analysis. As a post-session tool intended to support the understanding of teaching activities, the visualization in CoachVR introduced additional cognitive load but did not provide automated analysis to alleviate the burden that arises after interpreting the visualization. Therefore, simply presenting the visualization increased the participants' burden rather than creating a genuine need or motivation to use the tool for analyzing their own performance.

Chapter 6 Discussion

In this chapter, study design and visualization design in Teach-R/CoachVR will be discussed in the scientific context. Some part of this was already discussed in the Chapter 5, here a summary will be presented to conclude limitations and relations with other studies.

6.1 Discussion

6.1.1 The Heart Rate

From the aspect of physiological data

According to Hartanto (as cited in Wiepke, 2019)([Har24]), the original purpose of creating the Teach-R framework was to help teacher trainees practice classroom management and each session included two factions, coach and trainee, followed by a reflection afterwards. Teach-R has already collected some teacher behavior data (positional data, step data) and physiological data (eye tracking) to help teachers better understand their self-efficacy and improve their classroom management skills. As mentioned in **Section 2.1**, integrating physiological data can further strengthen users' sense of presence. In addition, in contrast to eye tracking, heart rate is a concept that is more readily comprehensible to general public. Under this premise, observing whether one's own heart rate is high or low is not unfamiliar to most people, and users can quickly understand their own condition through heart rate. Certainly, different types of physiological data can be combined as studies, just as in the previously mentioned research that integrates respiration and heart rate (cf. [DCL+24], [CSV24]). For example, eye tracking and heart rate can be integrated to help users understand where their gaze tends to be directed unconsciously when their heart rate is elevated. Alternatively, when the user's heart rate rises, a prompt could be displayed at the point of gaze to remind the teacher trainee to relax and breathe.

From the aspect of biofeedback

As mentioned in **Section 2.2**, in addition to being a form of physiological data, heart rate can also serve as a source of biofeedback. The current heart rate display in Teach-R simply uses different colors for distinction, and as a means for users to read their own physiological state, it still lacks more in-depth analysis or more intuitive biofeedback.

The presence of heart rate monitoring was relatively weak. This can be explained from two perspectives. On the one hand, the study aimed to investigate whether users could understand the role of heart rate in the learning analytics process, so the purpose of heart rate display was not fully explained to them. In addition, to maintain immersion, the heart rate display appeared more like an optional feature. On the other hand, the visualization itself did not provide systematic guidance or references to help users explore their own heart rate performance.

6.1.2 User Study and User Experience

Bias in UEQ

According to the UEQ handbook [1], the scales range from –3 (horribly bad) to +3 (extremely good). However, in practical applications, observed values typically fall within a narrower range. This is because mean scores are calculated across participants with diverse opinions and response tendencies (e.g., a tendency to avoid extreme categories).
As a result, it is highly unlikely to obtain values above +2 or below –2. Both systems scored higher on pragmatic quality than on hedonic quality. However, since the number of participants in the user study was relatively small, the distribution of user ratings was less consistent. One possible reason is that participants were not informed beforehand about the potential connection between heart rate and student behavior, which may have caused confusion during the experiment and consequently lowered their evaluation of hedonic quality. As stated in **Section 5.1.2**, most participants had little to no teaching experience, and the scenario of acting as an exam proctor was not sufficient to capture their full attention. Allowing them to engage in actual teaching tasks might have been a more effective way to sustain their seriousness and involvement.

6.1.3 The SmartWatch and Visualization in Teach-R

A smartwatch-style model with real-time heart rate display was implemented. As discussed in Related Work, immersion is a crucial aspect of VR, and introducing non-realistic logic could potentially break it. Decisions such as whether to display heart rate in VR, whether it should remain constantly visible, whether to display it in 3D or in 2D, and how to design the visualization chart were all difficult to make.

The smartwatch should be interactive

As mentioned in **Section 5.2.2**, while the concept of using smartwatch to display heart rate visualization was easy for participants to understand, their overall attention to it during the task appeared somewhat limited. There are suggestions regarding the smartwatch itself, such as designing it as an interactive device rather than a purely passive display. The interaction could be realized through haptic feedback or gesture control within the current Teach-R system. This is aligned with HCI principles noted in **Section 2.3**, reducing operational complexity and cognitive load can be achieved by designing simplified, intuitive interactions aligned with users' needs and habits (cf. [Zen24]).

Consider the personalized feature: Personal habit and personalized content

The placement of the smartwatch can also be considered during user study. A questionnaire survey revealed that among 2437 Korean participants 5.8% were left-handed and 7.9% were ambidextrous (cf. [JJ09]). In our user study, all participants were right-handed, and they were accustomed to raising their left hand to check their watch. For different habits, a simple approach would be to provide an option within the scenario to ask about it. Yet, following the HCI principles, one should consider setting up a simple task, such as a teleport function, allowing the Teach-R system to automatically determine which hand the participant prefers to use. These interaction

[1] See *UEQ handbook* at `https://www.ueq-online.org/Material/Handbook.pdf`

methods could provide preliminary support for extending smartwatch functionalities suggest by participants, such as adding a timer.

Similarly, HCI principles can also inform the design of smartwatch visualizations. In the user study, participants' heart rates remained relatively stable, resulting in only minor variations across zones. As a consequence, feedback based on color schemes was difficult for them to perceive. To address this issue, heart rate zones should be individually predicted and tailored for each user, ensuring that the visualization highlights meaningful variations in their physiological responses. This can link to **Section 2.4**, while heart rate provides an accessible and easy-to-understand indicator for users, HRV offers a possible measure of the relationship between cardiac activity and stress (cf. [FARBG16]). Therefore, HRV can be used as a valuable background analysis tool, helping present heart rate zone and complementing it with deeper insights into the stress and physiological states of users.

The environmental elements in Teach-R as a visualization

In addition to the smartwatch visual overlay, there are other possibilities for visualizing heart rate in Teach-R. As noted in **Section 2.2** and in **Section 3.1.1**, changes in the classroom environment represent a promising approach, as they do not interfere with the primary task of teaching activities. As several studies discussed in **Section 3.1.1**, environment-related biofeedback linked to heart rate can at least exert a positive effect (cf. [CSV24]). In research on virtual bicycle racing games([HWO+25]), the background of the environment scene was used to indicate heart rate levels, helping users return more effectively to the optimal heart rate zone. Without interfering with the teaching activities, elements in the Teach-R environment can be utilized as biofeedback for heart rate. Within Teach-R as a large-scale environment, features such as the lighting conditions inside the classroom or the weather and visibility outside can be considered as potential modalities for delivering biofeedback. Even the appearance of the smartwatch itself, such as its color and saturation, can serve as a form of biofeedback.

6.1.4 The Visualization in CoachVR

A Line Chart for heart rate, a Gannt Chart for student behavior, and a Seat Chart for seating plan was implemented. The visualization in CoachVR was evaluated as useful and intuitive, but overall it lacked sufficient user guidance and the connections between different pieces of information were limited. Gantt Chart was considered as the most intuitive visualization, except for the suggestion to adjust modifying the order of information displayed in the Hover Window.

Improvements for heart rate chart

Regarding the Line Chart, the connection between heart rate and student behavior should be presented through a structured system analysis to guide users' interpretation and reduce their cognitive load. This suggestion aligns with potential post-session feedback mechanisms that can be observed in the **Section 2.6**. For example, the heart rate line chart could incorporate analyses of intervention speed within specific intervals of student behavior.

Change the seat chart into a replay system

Regarding the Seat Chart, participants' feedback was not very positive. On the one hand, the absence of student names in Teach-R reduced their spatial impression of the classroom. On the other hand, the data presentation in the Seat Chart was not sufficiently intuitive, as it displayed aggregated statistics of each student's behavior over a period of time rather than their behavior at a specific timestamp. Consistent with one of the goals of Learning Analytics, this visualization aims to support users in recalling the session content. As introduced in **Section 2.7**, the previous voice analysis study(cf. [Rec25]) implemented a Teacher Clone to replay users' speech, providing a complementary approach to facilitating reflection. Similarly, one potential improvement for this visualization is to extend its functionality to support replay of the entire session. Heart rate, student behaviors, and teacher position could be played or paused simultaneously, allowing users to better observe and reflect on the dynamics of the whole session.

6.2 Limitations

Due to time and technical constraints, some planned goals and developments could not be implemented.

Most participants had little to no teaching experience, and therefore their feedback on the classroom scenarios was inevitably constrained by their own limited perspectives. In addition, since the user study scenario description lacked sufficient immersion, it is questionable whether participants were fully psychologically engaged during the Teach-R session.

Student behavior is not the only factor

What makes the issue more complex is that multiple independent variables can influence heart rate, relying solely on student behavior for analysis is clearly insufficient. Other factors, such as the teacher's physical condition, emotional state, and self-efficacy in the classroom environment, should also be taken into account. Incorporating these variables would provide a more comprehensive and reliable understanding of heart rate dynamics during teaching activities. Relying solely on heart rate as an indicator of stress is clearly insufficient, as stress is a multidimensional construct that requires additional physiological and behavioral measures for a more reliable assessment. HRV would serve as a valuable complementary measure for assessing stress, as it provides deeper insight into autonomic nervous system activity. Unfortunately, HRV was not employed in the current study.

Need to improve the transmission mechanisms

With regard to data transmission, the current mechanism in Teach-R poses certain limitations. Although all session data are stored in the LRS, retrieving them requires manual adjustments in Unity Inspector and restarting Teach-R, which makes the process inefficient. In addition, CoachVR lacks a dedicated interface for querying specific session data, further restricting smooth access and systematic analysis of teaching activities.

Improve the presence of heart rate during session

The heart rate display in Teach-R aimed to reduce users' sense of detachment from Teach-R by displaying heart rate information. However, since the display was not forced within the user's field of view, it was often overlooked. Although the visual overlay method provides an intuitive form of presentation, it still lacked sufficient salience to effectively capture users' attention. The visualization in CoachVR generally lacks clear guidance and does not provide systematic reporting feedback to help users evaluate their own teaching performance.

As mentioned earlier in **Section 2.7**, other statements regarding learning analytics in Teach-R have not yet been integrated with heart rate data. In particular, combining heart rate with other physiological measures, such as eye tracking (RFC 2023, RWTH Aachen University), should have provided a more powerful form of biofeedback.

6.3 Future Improvements

According to suggestions from user study participants, the primary and most important task is to integrate system-level feedback and guidance on heart rate activity and student behavior into CoachVR, serving as a reference for users' self-assessment. As mentioned in **Section 5.2.2 and Section 5.3.5**, they can help users understand the visualization and reduce the cognitive load. As shown in Figure 6.1, it is an example idea of displaying the most important student behavior in terms of heart rate fluctuation.

Figure 6.1: Improvement: A possible systematic analysis of heart rate and important student behaviors (randomly generated analysis content, top-left)

Biofeedback via environmental changes relies on personalized heart rate zones

The visualization in Teach-R is visual overlay on the smartwatch-styled screen. This has been discussed in **Section 6.1.3**, the presence of heart rate in the form of visual overlay is perceived as very limited. Within the Teach-R scenario, changes in weather or lighting could serve as mechanisms for conveying heart rate biofeedback. As noted in **Section 2.2**, receiving feedback on one's physiological signals can have positive effects. This visualization method ensures that users are subtly reminded of their current heart rate while minimizing interference with teaching activities. To implement this type of visualization, we need to define personalized heart rate ranges for each user, dividing them into high, medium, and low (or more fine-grained) zones, which can then be mapped to different environmental changes. Such personalized heart rate ranges require a baseline measurement to record the user's heart rate in a calm state.

Both of the improvements mentioned above could be enhanced by incorporating HRV as an analytical tool. As introduced in **Section 2.4**, HRV represents a valid and objective indicator of stress. To obtain more detailed and accurate insights into heart rate dynamics, HRV can be incorporated as a complementary measure, integrated into either real-time or post-session visualizations.

Seat chart as a replay system

Another improvement concerns the Seat Chart in CoachVR visualization, particularly its use for session replay. Replay is a core feature of Learning Analytics, supporting users in recalling and self-assessing their teaching activities. To achieve this, the current Seat Chart functionality would need to be adapted so that it no longer participates in data synchronization with other charts. Instead, it functions solely as a session replay module and allows the playback of heart rate patterns, student behaviors, and teacher positions throughout the session.

For cases of poor contact with the heart rate sensor, the visualization design should also incorporate more appropriate real-time feedback. According to the feedback principles proposed in HCI principles, vibration through the VR controller could be used as a way of feedback.

Chapter 7 Conclusion

The goal of the thesis was to integrate heart rate into the educational VR application Teach-R, helping teacher trainees to monitor their heart rate status during/after the Teach-R session and to provide data feedback. As new teachers may feel nervous in teaching scenarios, the purpose of the heart rate is to provide feedback on their own physiological characteristics, helping them better evaluate their performance. To achieve this goal, a heart rate sensor, OmiLAXR, and xAPI were used to record and transmit heart rate data.

Bar chart, segment guage chart and heart rate readout in different colors were created in Teach-R on a smartwatch-styled game object to help present real-time heart rate monitoring. During the Teach-R process, teachers can voluntarily raise their hand to check their heart rate. Line chart, Gannt chart and seat plan of students were created in the CoachVR dashboard page to help post-session feedback. After the Teach-R session, they are able to review the overall heart rate changes to gain an understanding of their general heart rate condition. To help teachers recall the content of the session, both heart rate visualization and student behavior can be reviewed simultaneously in order to explore the relationship between the two. To leverage users' spatial memory of the session, the heart rate visualization can be combined with the seating plan and students' behavioral data, allowing users to review a general overview of each student within a selected time interval.

A user study was conducted to evaluate the usability of visualizations in Teach-R and CoachVR. The results demonstrated that they are generally a practical tool for providing heart rate information in the context of educational training. However, the results suggested that Teach-R visualization should enhance the presence of heart rate visualization and CoachVR visualization should provide clearer guidance and more systematic analysis. At last, both systems scored higher on pragmatic quality than on hedonic quality, suggesting that users consistently valued their usefulness more than the enjoyment. This indicates that future work should also focus on making the visualizations more engaging and reducing users' cognitive load.

Currently, the visualization is limited to heart rate data. In the future, other behavioral data such as position and physiological measures such as eye tracking could be integrated with heart rate to provide richer insights. Moreover, the visualization of physiological data in Teach-R could also be explored through environmental factors to present biofeedback in a less disruptive yet meaningful way.

Appendix A Bibliography

[AHBI17] Fereshteh Amini, Khalad Hasan, Andrea Bunt, and Pourang Irani. Data representations for in-situ exploration of health and fitness data. In *Proceedings of the 11th EAI International Conference on Pervasive Computing Technologies for Healthcare*, PervasiveHealth '17, page 163–172, New York, NY, USA, 2017. Association for Computing Machinery.

[AKH+24] Daniel Anheuer, Brid Karacan, Lara Herzog, Nora Weigel, Silja Meyer-Nieberg, Thomas Gebhardt, Jessica Freiherr, Martin Richter, Armin Leopold, Monika Eder, Marko Hofmann, Karl-Heinz Renner, and Cornelia Küsel. Framework for microdosing odors in virtual reality for psychophysiological stress training. *Sensors*, 24(21), 2024.

[AM23] Ashraf Alam and Atasi Mohanty. Implications of virtual reality (vr) for school teachers and instructional designers: An empirical investigation. *Cogent Education*, 10(2):2260676, 2023.

[AMRH+24] Ibis Alvarez, Borja Manero, Alejandro Romero-Hernandez, Miriela Cardenas, and Isabel Masó. Virtual reality platform for teacher training on classroom climate management: evaluating user acceptance. *Virtual Reality*, 28, 03 2024.

[AV24] Jacqueline Anton and Mark J. Van Ryzin. Reducing teacher stress and burnout and enhancing self-efficacy through technology-supported small-group instruction. *Social and Emotional Learning: Research, Practice, and Policy*, 4:100053, 2024.

[Bai18] Jeremy Bailenson. *Experience on Demand: What Virtual Reality Is, How It Works, and What It Can Do.* W. W. Norton & Company, 2018.

[BC23] Philipp Beuchel and Colin Cramer. Heart rate variability and perceived stress in teacher training: Facing the reality shock with mindfulness? *Global Advances in Integrative Medicine and Health*, 12:1–16, 2023.

[BCDNLG+20] Mario Bocos-Corredor, Alejandro Diaz-Nieto, Álvaro López García, Alejandro Romero-Hernandez, Ibis Alvarez Valdivia, and Borja Manero. A vr game to improve communication skills in secondary-school teachers. pages 8701–8710, 07 2020.

[BI23] Sagi Baigabulov and Madina Ipalakova. Virtual reality enabled immersive data visualization for data analysis. In *Proceedings of the 8th International Conference on Digital Technologies in Education, Science and Industry (DTESI 2023)*, Almaty, Kazakhstan, 2023. CEUR Workshop Proceedings. Available under Creative Commons License Attribution 4.0 International (CC BY 4.0).

[Bla21] Tanja Blascheck. Glanceable visualizations for personal mobile devices. In Uta Hinrichs and Sheelagh Carpendale, editors, *Mobile Data Visualization*, pages 113–135. Springer International Publishing, 2021.

[BRG19] Johannes Blum, Christian Rockstroh, and Anja S. Göritz. Heart rate variability biofeedback based on slow-paced breathing with immersive virtual reality nature scenery. 10:2172, 2019.

[CHZ22] Esmeralda Campos, Irving Hidrogo, and Genaro Zavala. Impact of virtual reality use on the teaching and learning of vectors. *Frontiers in Education*, Volume 7 - 2022, 2022.

[CKCX+21] Joe Cecil, Sam Kauffman, Aaron Cecil-Xavier, Avinash Gupta, Vern McKinney, and Mary Sweet-Darter. Exploring human-computer interaction (hci) criteria in the design and assessment of next generation vr based education and training environments. pages 524–525, 03 2021.

[CMD+25] Andrea Calderone, Vincenza Maura Mazzurco Masi, Rosaria De Luca, Antonio Gangemi, Mirjam Bonanno, Daniela Floridia, Francesco Corallo, Giovanni Morone, Angelo Quartarone, Maria Grazia Maggio, and Rocco Salvatore Calabrò. The impact of biofeedback in enhancing chronic pain rehabilitation: A systematic review of mechanisms and outcomes. *Heliyon*, 11(2):e41917, 2025.

[CSV24] Luca Chittaro, Marta Serafini, and Yvonne Vulcano. Virtual reality experiences for breathing and relaxation training: The effects of real vs. placebo biofeedback. *International Journal of Human-Computer Studies*, 188:103275, 2024.

[DCL+24] Lucie Daniel-Watanabe, Benjamin Cook, Grace Leung, Marino Krstulović, J. Finnemann, Toby Woolley, Craig Powell, and Paul Fletcher. Using a virtual reality game to train biofeedback-based regulation under stress conditions. *Psychophysiology*, 62:e14705, 10 2024.

[DHH+15] Lisa Dieker, Michael Hynes, Charles Hughes, Stacey Hardin, and Kathy Becht. Tle teachlive™: Using technology to provide quality professional development in rural schools. *Rural Special Education Quarterly*, 34:11–16, 09 2015.

[Doy86] Walter Doyle. *Classroom Organization and Management*. Macmillan, 1986.

[EGH+25] A. Elnhofer, K. Goinska, J. Hattinger, et al. Virtual reality versus 2d biofeedback for children and adolescents with stress-related disorders: A randomized controlled trial. *Virtual Reality*, 29:46, 2025.

[Eke06] O. S. Ekere. *Concept of Disruptive Behaviour among Students in Public Secondary Schools*. Ekpeyong Publishers, Uyo, Nigeria, 2006.

[Eli11] Tanya Elias. Learning analytics. *Learning*, 1:22, 2011.

[ES01] Edmund Emmer and Laura Stough. Classroom management: A critical part of educational psychology, with implications for teacher education. *Educational Psychologist*, 36:103–112, 06 2001.

[EW06] Carolyn M. Evertson and Carol S. Weinstein. Classroom management as a field of inquiry. In Carolyn M. Evertson and Carol S. Weinstein, editors, *Handbook of Classroom Management: Research, Practice, and Contemporary Issues*, pages 3–15. Lawrence Erlbaum Associates, 2006.

[FARBG16] Philippe Fauquet-Alekhine, Laetitia Rouillac, Jérôme Berton, and Jean-Claude Granry. Heart rate vs stress indicator for short term mental stress. *British Journal of Medicine and Medical Research*, 17(7):1–11, 2016.

[FBR+23] Jan Francisti, Zoltán Balogh, Jaroslav Reichel, L'ubomír Benko, Kristián Fodor, and Milan Turčáni. Identification of heart rate change during the teaching process. *Scientific Reports*, 13:16674, 2023.

[FFC+25] H. Fang, C. Fang, Y. Che, X. Peng, X. Zhang, and D. Lin. Reward feedback mechanism in virtual reality serious games in interventions for children with attention deficits: Pre- and posttest experimental control group study. *JMIR Serious Games*, 13:e67338, 2025.

[Fim84] Michael J. Fimian. The development of an instrument to measure stress in teachers. *Journal of Clinical Psychology*, 40(2):310–325, 1984.

[FKK+10] Dana Frank, Lamees Khorshid, Jerome Kiffer, Christine Moravec, and Michael McKee. Biofeedback in medicine: who, when, why and how? *Mental Health in Family Medicine*, 7:85–91, 06 2010.

[FLE+25] M. Fusaro, M. P. Lisi, V. Era, et al. The transformative power of virtual reality: Redefining interactions in virtual platforms, education, healthcare, and workplaces. *Topoi*, 2025.

[FSBMG13] Jennifer Freeman, Brandi Simonsen, Donald Briere, and Ashley MacSuga-Gage. Pre-service teacher training in classroom management: A review of state accreditation policy and teacher preparation programs. *Teacher Education and Special Education The Journal of the Teacher Education Division of the Council for Exceptional Children*, 37:106–120, 05 2013.

[FSBMG14] Jennifer Freeman, Brandi Simonsen, Donald E. Briere, and Ashley S. MacSuga-Gage. Pre-service teacher training in classroom management: A review of state accreditation policy and teacher preparation programs. *Teacher Education and Special Education*, 37(2):106–120, 2014.

[GB23] Fairouz Grioui and Tanja Blascheck. Heart rate visualizations on a virtual smartwatch to monitor physical activity intensity. In *Proceedings of the 18th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2023) - Volume 3: IVAPP*, pages 101–114. SCITEPRESS – Science and Technology Publications, Lda., 2023. Under CC license (CC BY-NC-ND 4.0).

[GG20] Krista Vince Garland and Dennis Garland. Teachlive™ and teach well: Simulations in teacher education. In Elizabeth Bradley, editor, *Games and Simulations in Teacher Education*. Springer Nature Switzerland AG, 2020.

[GGP22] Janet K. Gibbs, Marco Gillies, and Xueni Pan. A comparison of the effects of haptic and visual feedback on presence in virtual reality. *International Journal of Human-Computer Studies*, 157:102717, 2022.

[GHS24] Sergej Görzen, Birte Heinemann, and Ulrik Schroeder. Towards using the xapi specification for learning analytics in virtual reality. In *Joint Proceedings of LAK 2024 Workshops, co-located with 14th International Conference on Learning Analytics and Knowledge (LAK 2024)*. CEUR Workshop Proceedings, 2024. Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

[GRCP19] Daniel Gromer, Max Reinke, Isabel Christner, and Paul Pauli. Causal interactive links between presence and fear in virtual reality height exposure. *Frontiers in Psychology*, Volume 10 - 2019, 2019.

[GVMS+16] A. Gaume, A. Vialatte, A. Mora-Sánchez, C. Ramdani, and F.B. Vialatte. A psychoengineering paradigm for the neurocognitive mechanisms of biofeedback and neurofeedback. *Neuroscience Biobehavioral Reviews*, 68:891–910, 2016.

[GWZE18] Stefan Gradl, Markus Wirth, Tobias Zillig, and Bjoern M Eskofier. Visualization of heart activity in virtual reality: A biofeedback application using wearable sensors. In *2018 IEEE 15th International Conference on Wearable and Implantable Body Sensor Networks (BSN)*, pages 152–155, 2018.

[Har20] Elizabeth Hartney. Stress management to enhance teaching quality and teaching effectiveness: A professional development framework for teachers. In *Occupational Stress*, pages 306–331. IGI Global, 2020.

[Har24] Jasmin Hartanto. Evaluating classroom management in VR using multi-modal learning analytics. Masterarbeit, RWTH Aachen University, Aachen, 2024. Veröffentlicht auf dem Publikationsserver der RWTH Aachen University; Masterarbeit, RWTH Aachen University, 2024.

[HL21] Andreas Halbig and Marc Erich Latoschik. A systematic review of physiological measurements, factors, methods, and applications in virtual reality. *Frontiers in Virtual Reality*, Volume 2 - 2021, 2021.

[HRKR21] Yizhen Huang, Eric Richter, Thilo Kleickmann, and Dirk Richter. Virtual reality in teacher education from 2010 to 2020: A review of program implementation, intended outcomes, and effectiveness measures. *Preprint*, December 2021.

[HRKR22] Yizhen Huang, Eric Richter, Thilo Kleickmann, and Dirk Richter. Class size affects preservice teachers' physiological and psychological stress reactions: An experiment in a virtual reality classroom. *Computers Education*, 184:104503, 2022.

[HS23] Birte Heinemann and Ulrik Schroeder. *Learning Analytics and Classroom Management in Specialized Environments: Enhancing the VR Classroom for CS Teacher Education*, pages 37–52. 10 2023.

[HWO+25] Oliver Hein, Sandra Wackerl, Changkun Ou, Florian Alt, and Francesco Chiossi. At the speed of the heart: Evaluating physiologically-adaptive visualizations for supporting engagement in biking exergaming in virtual reality. 08 2025.

[ILQC18] Petra Isenberg, Bongshin Lee, Huamin Qu, and Maxime Cordeil. *Immersive Visual Data Stories*, pages 165–184. Springer International Publishing, Cham, 2018.

[Ing01] Richard M. Ingersoll. Teacher turnover and teacher shortages: An organizational analysis. *American Educational Research Journal*, 38(3):499–534, 2001.

[JJ09] Hwa Jung and Hyung-Shik Jung. Hand dominance and hand use behaviour reported in a survey of 2437 koreans. *Ergonomics*, 52:1362–71, 11 2009.

[Kat21] Jozsef Katona. A review of human–computer interaction and virtual reality research fields in cognitive infocommunications. *Applied Sciences*, 11(6), 2021.

[KCB+18] Hye-Geum Kim, Eun-Jin Cheon, Dai-Seg Bai, Young Hwan Lee, and Bon-Hoon Koo. Stress and heart rate variability: A meta-analysis and review of the literature. *Psychiatry Investigation*, 15(3):235–245, 2018.

[KGB+22] Oswald D. Kothgassner, Andreas Goreis, Isabelle Bauda, Lisa M. Glenk, Ilse Kryspin-Exner, and Anna Felnhofer. Virtual reality biofeedback interventions for treating anxiety. *Wiener Klinische Wochenschrift*, 134(Suppl 1):49–59, 2022.

[KWN+23] J. I. Kerr, R. P. Weibel, M. Naegelin, et al. The effectiveness and user experience of a biofeedback intervention program for stress management supported by virtual reality and mobile technology: a randomized controlled study. *BMC Digital Health*, 1(42), 2023.

[LF22] Robin Lüddecke and Anna Felnhofer. Virtual reality biofeedback in health: A scoping review. *Applied Psychophysiology and Biofeedback*, 47, 03 2022.

[LFH12] Barry W. Lavay, Ron French, and Hester L. Henderson. Behavior management instructional practices and content of college/university physical education teacher education (pete) programs. *Physical Educator*, 69(2):137–150, 2012.

[LGRM08] F. A. Lopez, A. Gonzalez, M. Rodriguez, and C. Martin. The impact of student misbehavior on teacher stress and burnout. *Revista de Psicología Educativa*, 14(2):123–135, 2008.

[LLH+16] Jean-Luc Lugrin, Marc Erich Latoschik, Michael Habel, Daniel Roth, Christian Seufert, and Silke Grafe. Breaking bad behaviors: A new tool for learning classroom management using virtual reality. *Frontiers in ICT*, 3:26, 2016.

[LTW+18] Jiaying Liu, Tao Tang, Wei Wang, Bo Xu, Xiangjie Kong, and Feng Xia. A survey of scholarly data visualization. *IEEE Access*, PP:1–1, 03 2018.

[Mar90] Maeve Martin. *The Development and Evaluation of a Resource on Classroom Management Suitable for Use in Teacher Education*. Phd thesis, Institute of Education, University of London, January 1990.

[MJL96] Christina Maslach, Susan E. Jackson, and Michael P. Leiter. *Maslach Burnout Inventory Manual*. Consulting Psychologists Press, Palo Alto, CA, 3rd edition, 1996.

[MLF09] Christopher J. McCarthy, Richard G. Lambert, and Christopher Fitchett. Assessing teachers' appraisal of classroom resources and demands: The classroom appraisal of resources and demands. *Psychology in the Schools*, 46(10):1067–1082, 2009.

[OEC20] OECD. *TALIS 2018 Results (Volume II): Teachers and School Leaders as Valued Professionals*. OECD Publishing, 2020.

[OH21] James H. Oliver and James H. Hollis. Virtual reality as a tool to study the influence of the eating environment on eating behavior: A feasibility study. *Foods*, 10(1), 2021.

[OI16] Masataka Okabe and Kei Ito. Color universal design (cud): How to make figures and presentations that are friendly to colorblind people, 2016. Accessed: 2025-06-05.

[OR10] Regina M. Oliver and Daniel J. Reschly. Special education teacher preparation in classroom management: Implications for students with emotional and behavioral disorders. *Behavioral Disorders*, 35(3):188–199, 2010.

[Pos13] May Britt Postholm. Classroom management: What does research tell us? *European Educational Research Journal*, 12(3):389–402, 2013.

[Qin24] Haiyan Qin. Stress level of a classroom instructors and its influence to their classroom performance. *World Journal of Educational Research*, 11:p29, 01 2024.

[Rec25] Jona Recker. Voice in Teach-R. Masterarbeit, RWTH Aachen University, Aachen, 2025. Veröffentlicht auf dem Publikationsserver der RWTH Aachen University; Masterarbeit, RWTH Aachen University, 2024.

[RK95] Carol D. Ryff and Corey Lee M. Keyes. The structure of psychological well-being revisited. *Journal of Personality and Social Psychology*, 69(4):719–727, 10 1995.

[SA15] Fatma Sadik and Tugay Akbulut. An evaluation of classroom management skills of teachers at high schools (sample from the city of adana). *Procedia - Social and Behavioral Sciences*, 191, 06 2015.

[Sac14] Jerzy Sacha. Interaction between heart rate and heart rate variability. 19(3):207–216, 2014.

[SCL+22] Sean Sanford, Brian Collins, Mingxiao Liu, Sophie Dewil, and Raviraj Nataraj. Investigating features in augmented visual feedback for virtual reality rehabilitation of upper-extremity function through isometric muscle control. *Frontiers in Virtual Reality*, Volume 3 - 2022, 2022.

[SCRJ23] Kwang-Seong Shin, Chungyeon Cho, Ji Hyun Ryu, and Dongsik Jo. Exploring the perception of the effect of three-dimensional interaction feedback types on immersive virtual reality education. *Electronics*, 12(21), 2023.

[Sel36] Hans Selye. A syndrome produced by diverse nocuous agents. *Nature*, 138:32, 1936.

[SF18] Christian Spoden and Kai Fricke. Measurement of teachers' reactive, preventive and proactive classroom management skills by student ratings – results from a two-level confirmatory factor analysis. *Psychological Test and Assessment Modeling*, 60:223–240, 2018.

[Sha96] Mike Sharples. *Human-Computer Interaction*, pages 293–323. 12 1996.

[SLA24] Dariyash Shakimova, Kehinde Lawrence, and Zhanat Aubakirova. Professional development training can help teachers to build resistance against teaching associated stress. *Cogent Education*, 11, 05 2024.

[Sof25] Rustici Software. xapi (experience api) overview, 2025.

[SS16] Einar M. Skaalvik and Sidsel Skaalvik. Teacher stress and teacher self-efficacy as predictors of engagement, emotional exhaustion, and motivation to leave the teaching profession. *Creative Education*, 7:1785–1799, 2016.

[TMH07] Megan Tschannen-Moran and Anita Woolfolk Hoy. The differential antecedents of self-efficacy beliefs of novice and experienced teachers. *Teaching and Teacher Education*, 23(6):944–956, 2007.

[TSR25] Stefano Triberti, Caterina Sapone, and Giuseppe Riva. Being there but where? sense of presence theory for virtual reality applications. *Humanities and Social Sciences Communications*, 12, 01 2025.

[WH24a] Axel Wiepke and Birte Heinemann. A systematic literature review on user factors to support the sense of presence in virtual reality learning environments. *Computers Education: X Reality*, 4:100064, 2024.

[WH24b] Shelley Woodall and James H. Hollis. The difference between pc-based and immersive virtual reality food purchase environments on useability, presence, and physiological responses. *Foods*, 13(2), 2024.

[WMS22] Axel Wiepke, Lisa Müller, and Peter Schmidt. Das vr-labor-klassenzimmer zur professionalisierung von lehramtsstudierenden der chemie. *Journal of Teacher Education in Science*, 35(4):200–220, 2022.

[WPH24] Wei-Sheng Wang, Margus Pedaste, and Yueh-Min Huang. The impact of feedback mechanism in vr learning environment. In Yu-Ping Cheng, Margus Pedaste, Emanuele Bardone, and Yueh-Min Huang, editors, *Innovative Technologies and Learning*, pages 134–142, Cham, 2024. Springer Nature Switzerland.

[WPH+25] Danping Wang, Yunchao Peng, Lise Haddouk, Nicolas Vayatis, and Pierre-Paul Vidal. Assessing virtual reality presence through physiological measures: a comprehensive review. *Frontiers in Virtual Reality*, Volume 6 - 2025, 2025.

[WRLH24] Andrea Westphal, Eric Richter, Rebecca Lazarides, and Yizhen Huang. More i-talk in student teachers' written reflections indicates higher stress during vr teaching. *Computers Education*, 212:104987, 2024.

[WRZR19] Axel Wiepke, Eric Richter, Raphael Zender, and Dirk Richter. *Einsatz von Virtual Reality zum Aufbau von Klassenmanagement-Kompetenzen im Lehramtsstudium*, page 133. 09 2019.

[Zen24] Qingliang Zeng. Research on human computer interaction technology in virtual reality scenes. *Academic Journal of Science and Technology*, 11:237–241, 06 2024.

[ZPB+24] Stephanie Zito, Julia Petrovic, Bilun N. Böke, Isabel Sadowski, Dana Carsley, and Nancy L. Heath. Exploring the stress management and well-being needs of pre-service teachers. *Teaching and Teacher Education*, 152:104805, 2024.

[İl07] Levent İlgar. *İlköğretim öğretmenlerinin sınıf yönetimi becerileri üzerine bir araştırma*. Doctoral dissertation, İstanbul Üniversitesi, Turkey, 2007.

Appendix B Digital Appendix

The digital appendix is submitted as CodesAndFiles.zip file. For more details of this material please contact the author or LuFG i9.

Zentrales Prüfungsamt/Central Examination Office

RWTH AACHEN UNIVERSITY

Eidesstattliche Versicherung
Declaration of Academic Integrity

Huang, Pu

Name, Vorname/Last Name, First Name

414498

Matrikelnummer (freiwillige Angabe)
Student ID Number (optional)

Ich versichere hiermit an Eides Statt, dass ich die vorliegende Arbeit/Bachelorarbeit/Masterarbeit* mit dem Titel
I hereby declare under penalty of perjury that I have completed the present paper/bachelor's thesis/master's thesis* entitled

Heart Rate in Multimodal Learning Analytics in Educational Virtual Reality

selbstständig und ohne unzulässige fremde Hilfe (insbes. akademisches Ghostwriting) erbracht habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt; dies umfasst insbesondere auch Software und Dienste zur Sprach-, Text- und Medienproduktion. Ich erkläre, dass für den Fall, dass die Arbeit in unterschiedlichen Formen eingereicht wird (z.B. elektronisch, gedruckt, geplottet, auf einem Datenträger) alle eingereichten Versionen vollständig übereinstimmen. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.
independently and without unauthorized assistance from third parties (in particular academic ghostwriting. I have not used any other sources or aids than those indicated; this includes in particular software and services for language, text, and media production. In the event that the work is submitted in different formats (e.g. electronically, printed, plotted, on a data carrier), I declare that all the submitted versions are fully identical. I have not previously submitted this work, either in the same or a similar form to an examination body.

Aachen, September 21, 2025

Ort, Datum/City, Date

Pu Huang

Unterschrift/Signature

*Nichtzutreffendes bitte streichen/Please delete as appropriate

Belehrung:
Official Notification:

§ 156 StGB: Falsche Versicherung an Eides Statt
Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.

§ 156 StGB (German Criminal Code): False Unsworn Declarations
Whosoever before a public authority competent to administer unsworn declarations (including Declarations of Academic Integrity) falsely submits such a declaration or falsely testifies while referring to such a declaration shall be liable to imprisonment for a term not exceeding three years or to a fine.

§ 161 StGB: Fahrlässiger Falscheid; fahrlässige falsche Versicherung an Eides Statt
(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.
(2) Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Abs. 2 und 3 gelten entsprechend.

§ 161 StGB (German Criminal Code): False Unsworn Declarations Due to Negligence
(1) If an individual commits one of the offenses listed in §§ 154 to 156 due to negligence, they are liable to imprisonment for a term not exceeding one year or to a fine.
(2) The offender shall be exempt from liability if they correct their false testimony in time. The provisions of § 158 (2) and (3) shall apply accordingly.

Die vorstehende Belehrung habe ich zur Kenntnis genommen:
I have read and understood the above official notification:

Aachen, September 21, 2025

Ort, Datum/City, Date

Pu Huang

Unterschrift/Signature

Acknowledgement

I would like to express my sincere gratitude to Professor Ulrik Schroeder for giving me the opportunity to write this thesis. I am also grateful to Birte Heinemann and Jasmin Hartanto for their patience and support during my development and thesis writing. My thanks further go to the LTI lab for their help, as well as to Sergej, Tobiasm and Hyperate Team, whose assistance was invaluable in solving difficult problems during the development process.