**# Introduction**

In the educational context, there is a particular interest in finding adequate indicators and quantitatively measurable parameters for teacher stress and burnout [@fisher2011; @ junker2021]. Previous research on teacher stress often focused on the psychological experience of stress using self-report questionnaires with single-item measures (“I find teaching to be very stressful‖”) [@chaplain2008; @goker2012] or questionnaires with multiple scales (e. g. Teacher Stress Inventory; @fimian1990; @liu2020]. However, self-reported data in the measurement of stress raises concerns about the validity and accuracy of causal inferences for several reasons, including response biases such as social desirability [@razavi2001self] or recall bias [@van2016accuracy]. Because self-reported data fail to capture actual physiological stress responses in real-life situations, ambulatory assessment methods using a variety of assessments are recommended e.g., collecting additional physiological measures such as HR as objective data [@trull2013ambulatory; @ wettstein2020ambulatory]. Furthermore, HR as a physiological measurement provides researchers with objective insights into teachers’ affectivity and stress levels without interrupting the teaching process [@donker2018; @runge2020].

In the last decade, commercial wearables have become increasingly popular and accepted among the wider population. The impact of these devices comes in concrete data: Valued at USD 61.30 billion in 2022, the market for wearable technology has experienced robust growth and is expected to continue to expand with an annual growth rate of 14.6% from 2023 to 2030 [@https://www.grandviewresearch.com/industry-analysis/wearable-technology-market]. International Data Corporation (IDC), a global provider of market research and advisory services for the technology industry, reports that the substantial growth in the wearable market has primarily been driven by smartwatches and wrist-worn fitness trackers [@richter2018global]. The most frequently used wearables in research projects are Fitbit, Garmin, Misfit, Apple, and Polar. These brands, already existing for several years, have shipped a substantial quantity of devices [henriksen2018using].

In addition to the ease of use, perceived usefulness, and enjoyment [@peng2022acceptance], the success of these devices is based on the fact that they are equipped with biosensors providing users with behavioral (e.g., step count, distance walked) and physiological data (e.g., HR, skin temperature). The general public is thus offered the opportunity to use low-cost, lightweight devices to monitor their physical activity and health routines in their everyday life. In contrast to occasional clinical observations, they allow the collection of big data over a longer period, whereby wrist-worn wearables are less intrusive than complex medical devices (e.g., electrocardiograms) that have to be attached to the body [@godfrey2018z].

The use of wearables has already been investigated across a wide range of domains, such as medicine [@hughes2023wearable; @yetisen2018wearables], sports [@secckin2023review; @ adesida2019exploring] or entertainment [@helmer2009smart; @cciccek2015wearable]. In educational contexts, research about the use of wearables is meager [@de2017towards].

While there are studies on how wearables can be used in the educational context to support teachers in monitoring student activity in the classroom [@quintana2016keeping; @de2017towards], there is a research gap on the use of wrist-worn wearables by teachers. Especially wrist-based fitness trackers, which are being used by a majority of the population, could offer the possibility of analyzing physiological parameters to gain deeper insights into the stress and strain experienced by teachers. HR measurements as a parameter – measured by most fitness trackers – are becoming increasingly important in research on stress experience as they offer insights into the cardiovascular system’s exertion levels in reaction to both physical and mental exertion [@sammito2015guideline]. Stress or mental and physical strain are factors that directly influence HR and lead to an increase in it [@custodis2014heart]. They represent an important physical and emotional stress indicator, as an increased workload is associated with increased HR [@sachs2014]. Furthermore, they allow a more objective recording of stress than for example self-reports without interrupting the teaching process [@donker2018; @runge2020].

To date, the studies measuring teachers’ HR in teaching-learning settings mostly use very expensive and intrusive electrocardiographs [@sperka1995; @scheuch1997psychophysische; @donker2018; @junker2021; @huang2022class], revealing that teacher-centered activities and typical stressors are leading to an increase in HR. @scheuch1997psychophysische, for example, assessed the HR of 67 teachers during five real lessons, with results showing that the highest HR occurred during organizational activities, followed by teaching activities where the teacher directed the interaction.

Other studies that have recorded HR using wearables have shown that HR decreases during a learning unit [@Darnell2019] and increases before induced stress tasks [@chalmers2021]. It should be noted that not teachers’ but college students’ HRs were assessed in these studies.

Accordingly, robust studies on whether wearable such as fitness trackers are efficient, low-cost, and robust measurements for assessing teachers’ physiological stress during teaching remain a desideratum. However, research on teacher stress is particularly relevant due to the increased stress levels in the teaching profession [@johnson2005experience]. @kieschke2008professional revealed that German teachers tend to show an “excessive commitment coupled with inadequate coping resources; and […] are too exhausted to be capable of big efforts” (p. 435). One of the reasons for this is that teachers are confronted with a multitude of demands in their everyday work, some of which exceed their available resources and therefore make it difficult to cope with various stressors [@montgomery2005meta]. In particular, the unpredictability of events such as classroom disruptions during lessons are typical stressors and can be very overwhelming for teachers.

Stress therefore occurs when stressors accumulate [@mann2021cumulative], although the extent of the strain depends on the subjective appraisal of the objective demands placed on the individual about available resources [@kyriacou2001]. It is therefore particularly important for teachers in the teaching profession to have sufficient personal and professional resources at their disposal [@cramer2018belastung], whereby, for example, professional knowledge about classroom management reduces the risk of stress [@klusmann2012berufliche]. Teachers’ characteristics such as professional experience in turn have an impact on the development of classroom management skills and thus also on the appraisal processes, as these skills develop during professional experience [@ophardt2017klassenmanagement; @wolff2015keeping].

To better understand how stressors like classroom disruptions affect teachers and their responses, it would be helpful for educational researchers to track teachers’ HR using affordable and non-intrusive tools like fitness trackers. This study investigated if wrist-based fitness trackers are useful to monitor teachers’ HR during a five-phase lab study, which included a micro-teaching unit. We also looked at whether teachers’ teaching experience and their assessment of disruptions and confidence in the classroom could explain differences in HR measurements.

**## Fitness Trackers as a Method to Assess HR as an Indicator of Stress**

Wearables (also referred to as wearable devices, wearable computers, or wearable electronics, @cciccek2015wearable) are defined as electronic devices that are either directly worn on the body or loosely attached to a person and integrated into clothing or accessories to serve as a convenient all-in-one solution [@godfrey2018z]. Essentially, wearables such as fitness trackers are designed to be worn continuously by users, gathering data such as location, movements, and vital signs via wireless sensors enabling users to interact with these devices anytime and anywhere [@cheng2017underlying]. These gadgets are characterized by attributes such as hands-free operatable, portable, useful, reliable, practical, multi-functional, mobile, socially acceptable, etc. [@cciccek2015wearable, p. 46].

In the last decades, fitness trackers have become widely popular and accepted as a mass product by the population [@park2020user]. Several factors contribute to widespread acceptance: Fitness trackers monitor various aspects of physical activity like HR, distance, steps, and calories burned, providing valuable insights into users’ daily activity and cardiovascular health, supporting them in setting personalized fitness and health goals [@nuss2021effects] or providing information about stress levels [@hao2018chrv]. Further advantages are the portable, non-invasive nature of these devices, the ease of use, and especially, the low costs compared to complex laboratory methods for determining vital parameters such as HR, blood pressure, skin temperature, or physical activity [@hajj2023].

The blend of these factors positions fitness trackers as an ideal technology for use not only in healthcare, entertainment, and fitness [sinha2019taxonomy] but also in education as they offer added benefits for formal and informal learning environments for both students and teachers [@de2017towards]. However, in most studies, the focus is on students, especially to detect students’ skills and enhance their performance [@koutromanos2020use]. Despite the enormous potential of wearables, there is a desideratum of studies that deal with important recorded parameters and in particular their significance for teachers.

One important health parameter assessed by most wrist wearables is HR measurement [@scalise2018wearables]. HR indicates the number of heartbeats within a certain time interval, which is usually heartbeats per minute and is therefore expressed in min-1 or beats per minute (BPM) [@hottenrott2007]. HR can be detected and measured using various methods via wearables, including sensors based on electrocardiogram (ECG) or phonocardiogram (PCG) [@mukhopadhyay2017wearable]. Another uncomplicated and inexpensive technique to measure HR via fitness trackers is photoplethysmography (PPG) [@castaneda2018review]. This optical method assesses HR by flashing green or red lights to measure changes in blood volume [@allen2007photoplethysmography].

Physiologically, HR is regulated and influenced on short-time intervals by the autonomic nervous system which is divided into two distinct components: the sympathetic and the parasympathetic nervous system [@pham2021]. An increase in the activity of the sympathetic, known as the “quick response” system, results in HR being speeded up (“fight or flight”) [@taelman2009influence]. Therefore, an increase in HR can be regarded as an indicator of increasing stress on the cardiovascular system as stress-induced excitation of the sympathetic nervous system leads to activation of the cardiovascular system [@kyriacou1978]. In contrast, increased activity of the parasympathetic as the counterpart known as the “relaxed response” system, has the effect of slowing down the HR (“rest and digest”) [@battipaglia2015]. At rest, the average HR of adults typically ranges from 60 to 80 BPM [@sammito2015guideline].

In addition to the autonomic nervous system and genetic factors, human HR is influenced by numerous external factors such as social, personal, psychological, environmental, and behavioral factors [@wang2022]. Furthermore, it depends largely on the intensity of strain “in response to physical and mental workload” [@sammito2015guideline, p. 1]. Physical and mental strain are therefore factors that directly influence HR and lead to an increase in HR [@custodis2014heart].

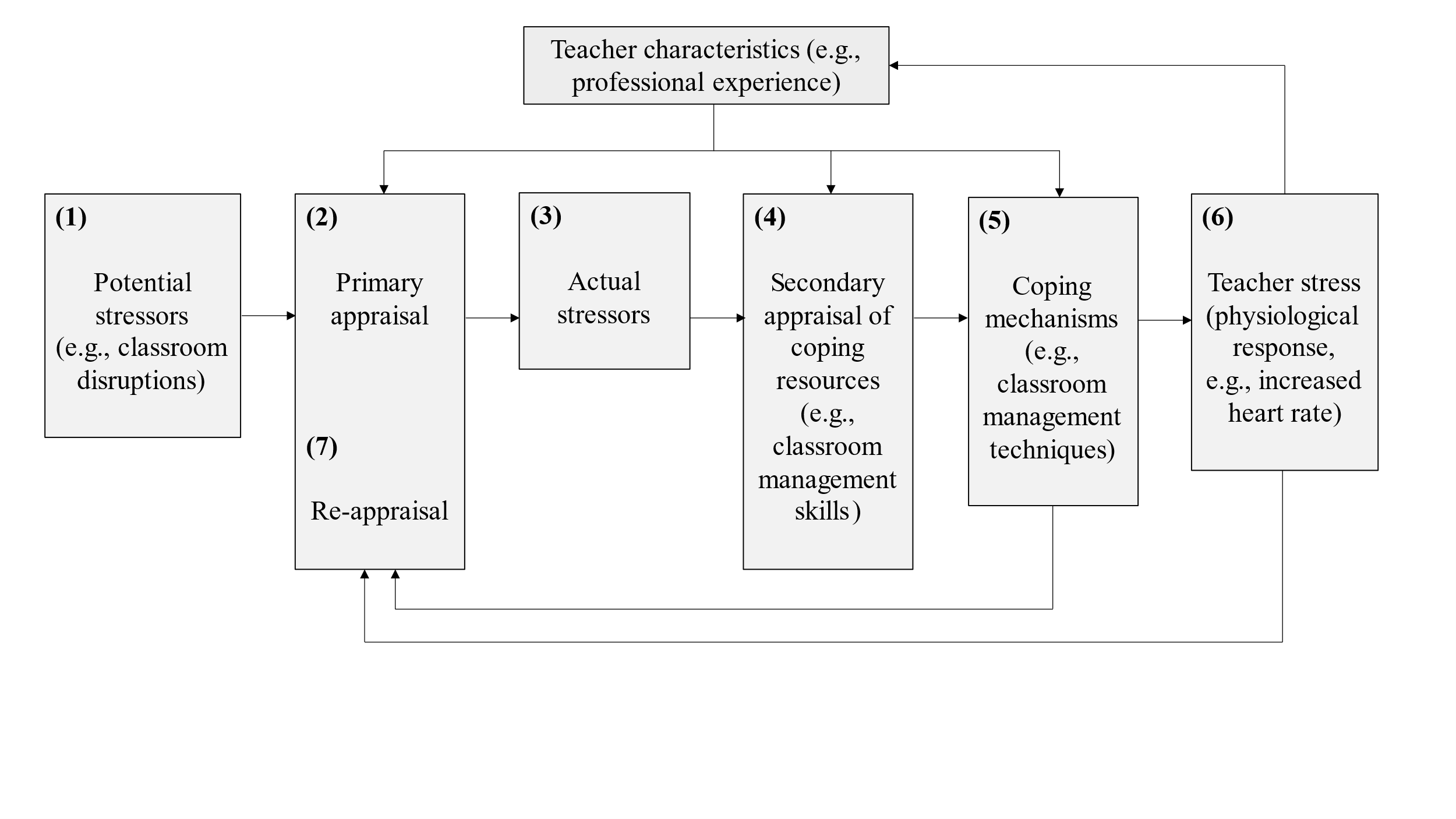
**## Teacher Stress and Important Resources**

An increased HR as an indicator of stress is particularly essential in the teaching-learning context, as the teaching profession is one of the most stressful professions compared to other occupational groups, facing a variety of stressors during everyday work [@smith2000; @herman2020; @schult2014belastet]. According to @kyriacou1978, teacher stress can be defined as

“a response of negative affect […] usually accompanied by potentially pathogenic physiological and biochemical changes (such as increased heart rate […]) resulting from aspects of the teacher’s job and mediated by the perception that the demands made upon the teacher constitute a threat to his self-esteem or well-being and by coping mechanisms activated to reduce the perceived threat.” (p. 2).

This definition of teacher stress is based on the ideas of the integrative framework of the transactional stress model by Lazarus and colleagues [@lazarus1981stressbezogene; @lazarus1984stress]. Lazarus’ stress theory initially served as a model, which @kyriacou1978 subsequently modified and tailored to the teaching-learning environment [@dick2013belastung]. For our study, we adapted the model of @van2006stress who made slight modifications to the model of @kyriacou1978.

In general, the model highlights the interaction between an individual and the environment, whereby stress refers to any event that exceeds a person's adaptive resources [@lazarus1990theory]. It has been shown that there are important connections between stress and resources on the one hand and stress-induced health issues on the other [@krause2013messung], which is why the investigation of teacher stress is highly relevant. As classroom disruptions are one of the most influential stressors and key risk factors for teacher health [@boyle1995structural; @aloe2014multivariate], the model will be explained using an example situation based on the relevance of the issue (see @dick2013belastung):



*Figure 1* A model of teacher stress (adapted from van Dick 2006, p.37, modified by the author)

A teaching unit with classroom demands such as classroom disruptions is an objective aspect of teachers’ work and represents potential occupational stress factors in the teaching profession (see Fig. 1, box 1; @karner2021teachers). When classroom disruptions occur, the first step is for teachers to subjectively appraise how disruptive the event is (see Fig. 1, box 2). A classroom disruption can therefore be perceived positively as a challenge, considered to be irrelevant, or negatively as a potential threat. The stress model only continues in the last case when potential stressors are evaluated as actual stressors (see Fig. 1, box 3).

In the next step, during the second subjective appraisal (see Fig. 1, box 4), teachers consider whether they have sufficient resources available to feel confident in dealing with the stressors. In the best case, teachers have both external (e.g., supportive colleagues) and internal (e.g., classroom management skills) resources at their disposal. A lack of resources and coping mechanisms can lead to negative personal and vocational consequences such as burnout, high turnover, and premature retirement [@jalongo2006; @unterbrink2007; @aloe2014]. These correlations are not surprising, as teaching is characterized as multidimensional, simultaneous, immediate, unpredictable, public, and shared [@doyle2013ecological]. Lessons and, in particular, classroom disruptions are unpredictable and multifaceted. All of these circumstances place several demands on teachers and require a high level of knowledge and competence from the teacher [@klieme2008concept]. These professional competencies encompass, among other things, teachers’ specific knowledge and skills about classroom management and can be understood as a diverse toolbox of strategies, techniques, and measures for the teacher to navigate the challenging environment of the classroom [@konig2016teacher].

Additionally, during both primary and secondary appraisal processes, teachers’ characteristics, such as teaching experience (see Fig. 1, upper box), play a particularly important role and have a decisive influence on classroom management skills. Particularly teachers with less teaching experience are overwhelmed by the simultaneity and complexity of teaching [@ophardt2017klassenmanagement; @wolff2015keeping; @ klusmann2012berufliche]. Skills in dealing with teaching events are closely related to the cognitive load of teachers. These classroom management skills develop, among other things, through growing teaching experience, as teachers attempt to cluster experienced classroom events into patterns and formulate appropriate action alternatives. According to @wolff2021classroom, such cognitive processes can be understood as mental classroom management scripts. Accordingly, especially for beginning teachers, the teaching profession seems to be very demanding and stressful. In particular the first five years, between 40 and 50 percent of beginning teachers change careers for a variety of reasons such as disciplinary problems with students [@ingersoll2003]. @fisher2011 investigated the extent to which age or teaching experience and job dissatisfaction are associated with an increased risk of burnout and stress among teachers. The results revealed that teachers with less professional experience had higher burnout scores and that years of professional experience, burnout, and satisfaction in the teaching profession are statistically significant predictors of teacher stress.

Based on the evaluation of resources and their characteristics, teachers will try to cope with classroom disruptions (see Fig 1., box 5) and, for example, use classroom management strategies to stop the disruption. If teachers are unable to cope, they experience stress (see Fig. 1, box 6). Teacher stress is mainly characterized as a reaction to negative affect (e.g., anger or depression), which is generally followed by other symptoms that can be seen as reactions to teacher stress. The response of negative affect can be among other things a physiological stress reaction, such as an increased HR [huang2022class; @kyriacou1978]. Based on the resource appraisal and the successful or unsuccessful coping with the stressor, the stressor will be appraised again (see Fig. 1, box 7).

For our research goals, we are particularly interested in potential stressors in the classroom such as classroom disruptions (see Fig. 1, box 1), the different appraisal processes, how disruptive disruptions are perceived (see Fig. 1, box 2), and how confident teachers feel in coping with them (see Fig. 1, box 4). In addition to the teaching experience (see Fig. 1, upper box), we want to investigate the impact of these aspects on the physiological component in terms of an increased HR (see Fig. 1, box 6), which can be interpreted as an indicator of stress based on existing research [@clays2011perception; @schubert2009effects].

**## HR in Teaching-Learning Contexts**

To better understand the interlinking of these facets and the cause of teacher stress, @wettstein2021 recommended measuring physiological parameters before, during as well as after teaching. For this reason, it is particularly important to look at the course of teachers’ HR, for example by recording measures not only during the teaching unit but also before and after the strain phase. In the following section, we will therefore outline certain studies relevant to our research question that recorded teachers’ HR, with studies first that used expensive and intrusive ECG, before moving on to studies that used wearables with PPG.

The results of the studies using ECG revealed that HR as an indicator of stress can be used to map different HR courses during teaching depending on the teachers’ activity. The HR increased especially during teacher-centered activities when teachers had to take a leading position in the student-teacher interaction [@sperka1995; @scheuch1997psychophysische; @donker2018; @junker2021]. @sperka1995 for example recorded the HR of 16 pre-service teachers during their first lesson. The results showed that the first lesson is linked to significantly increased psychophysiological activation in terms of an increased HR. The activation effect was particularly prominent at the beginning of the lesson and decreased over the course of the lesson due to the pre-service teachers’ active coping processes, meaning that the active management of the interaction with the students helped the teachers regulate their HR.

Other studies that also measured teachers’ HR using ECG identified typical potential predictors for increased HR values such as typical stressors, e.g., class size [@huang2022class] or low student engagement and motivation [@junker2021]. @junker2021 for example recorded the HR of 40 teachers using an Ambulatory Monitoring System with seven electrodes during a real classroom lesson to find out to what extent main stressors within the classroom (e.g., low student engagement and motivation, teacher-centered activities) can predict teachers’ HR as an indicator of physiological stress during teaching. @junker2021 provided evidence that teacher stress caused by those stressors during teaching can be quantitatively measured by an increase in HR.

In addition to these studies that measured HR using cost-intensive and intrusive ECG devices, there are a few studies that used low-cost, wrist-worn fitness trackers to investigate HR trends in teaching-learning situations [@Darnell2019; @chalmers2021]. @Darnell2019 for example measured the HRs of 15 medical college students using wrist-worn devices during lecture classes. The analysis revealed a constant decrease in HR from the beginning to the end of a lecture, whereas the HR peak was reached during active learning sessions. The researchers proposed the first robust measurements of HR changes during lectures and recommended using personal fitness trackers during various phases of learning and teaching. Even though the participants in the study were learners and did not teach any lessons themselves, the results are relevant for our study as it can be shown that a) HR can be recorded using fitness trackers in a learning unit and b) HR changes over the course of the learning unit during activating phases.

In another study, @chalmers2021 examined the usability of the average HR measured with a Fitbit fitness tracker of 30 medical students and 30 normative participants to identify physiological changes during stress tasks, whereas the average HR increased significantly between the resting and stress phases for both groups. However, it is important to note that these studies did not measure teachers’, but college students’ HR. This distinction is important since we looked at different HRs for teachers in our study, but it should be highlighted at this point that HR measurements can be recorded via fitness trackers to indicate HR changes.

So far, only one study has combined both aspects of recording teachers’ HR by wrist-worn wearables [@runge2020]: A Fitbit fitness tracker was used to assess HR as an indicator of stress in four teachers. They concluded that stress in the teaching profession can be mapped using fitness trackers’ indicators. In particular, it was found that the combination of a high number of steps, a high HR, and short sleep is an indicator of stress and that poor student behavior is the stressor that is perceived most frequently. It should be noted that the generalizability of the results is limited due to the small sample size of four participants.

The studies showed that the HR of teachers (and students) changed, depending on the activity and stressors during teaching, whereby teacher-centered phases in particular led to an increase in the HR. Furthermore, it could be shown that HR increases even before stress occurs.

**## Present Investigation**

The present investigation was part of a larger project targeting the development of professional vision in teachers. The study was carried out in a classroom at the university that served as the lab.

Within the time frame of approximately two hours, we distinguished five phases of our study: In the (1) pre-teaching phase, the participants were welcomed, prepared for the following micro-teaching unit, and familiarized with the setting. During the (2) teaching phase, the participants taught a 15-minute self-prepared micro-teaching unit to a "class" of three actors that performed nine (possibly disruptive) classroom events (e.g., chatting with a neighbor, heckling, looking at the phone; see Table ## in the supplementary material for an overview and categorization of all events; also see Fig## for a depiction of the laboratory setting of the micro-teaching unit). The actors received standardized instructions on a screen (only visible to the actors, but not to the participants) to perform a classroom event every one and a half minutes. While teaching, participants wore eye-tracking glasses, and additionally, their lessons were recorded by cameras. In the (3) post-teaching phase, the participants answered several questionnaires, followed by the (4) interview phase, in which they watched the video of their 15-minute unit and answered questions about the (disruptive) classroom events. In the (5) end phase, the participant answered another questionnaire. These conditions were identical for all participants.

During the entire study, the participants wore a fitness tracker, while the HR measurements provided the database for the present investigation. Previous research found that fitness trackers can be used as a low-cost, non-invasive method of measuring HR [hajj2022wrist; @fuller2020reliability] and that fitness trackers can help to detect differences in mean HR between different teaching phases [@donker2020associations; @junker2021potential]. However, XXX

Thus, the goals of the present study were twofold:

(1) The first research goal was to investigate whether HR measures assessed by wrist-based fitness trackers are a suitable and effective method for mapping teachers’ HR over the course of a five-phase lab study, including a micro-teaching unit.

In the first step, we therefore exploratively described the participants’ overall HR trend during the two-hour study interval and examined whether z-standardization of the participants’ mean HR can serve as a useful method to account for individual differences in baseline HR. Regarding the HR trend of the entire course of the study, we expected participants´ HR to gradually increase during the pre-teaching phase, to peak during the teaching phase, and to gradually decrease during the remaining time interval. Furthermore, we expected to observe the same trends in both standardized and non-standardized mean HR values.

In the second step, we selected five corresponding intervals with a length of ten minutes each out of the five phases and examined the levels of and the changes in HR of the five intervals separately. We presumed the highest HR levels in the micro-teaching unit and regarding HR changes, we expected an increase at the beginning of the study and a decrease in the following phases.

(2) The second research goal was to examine whether variance in HR measures can be explained by teachers’ teaching experience, and by self-reported cognitive appraisal (disruption appraisal and confidence appraisal) of classroom events. We expected all three variables (teaching experience, disruption appraisal, and confidence appraisal) to be significant predictors for the HR measurements in the different phases.