Measurement of Heart Rate and Heart Rate Variability with Wearable Devices: A Systematic Review

Fabian Josef Stangl
University of Applied Sciences Upper Austria, Steyr, Austria, Fabian.Stangl@fh-steyr.at

René Riedl
University of Applied Sciences Upper Austria, Steyr, Austria;Johannes Kepler University Linz, Linz, Austria, rene.riedl@fh-steyr.at

Measurement of Heart Rate and Heart Rate Variability with Wearable Devices: A Systematic Review

Fabian J. Stangl[1], René Riedl[1,2]

[1] University of Applied Sciences Upper Austria, Steyr, Austria
{fabian.stangl,rene.riedl}@fh-steyr.at
[2] Johannes Kepler University Linz, Linz, Austria

Abstract. Wearables are a ubiquitous trend in both commercial and academic settings as they easily enable tracking and monitoring of physiological parameters such as heart rate (HR) and heart rate variability (HRV). This paper presents a literature review to survey the existing Neuro-Information-Systems (NeuroIS) literature on HR and HRV with a focus on measurement based on wearable devices. We addressed the following four research questions: Who published HR and HRV research? What kind of HR and HRV research has been published? With which wearable devices was HR and HRV measured? How reliable and valid are HR and HRV measurements based on wearable devices? Our review provides answers to these questions and concludes that further efforts are needed to advance the field from both a theoretical and methodological perspective.

Keywords: Heart Rate (HR), Heart Rate Variability (HRV), Wearables, Accuracy, NeuroIS

1 Introduction

Digitalization, understood as the integration of technological innovations in all areas of daily life, has an impact at the societal, political, economic, organizational, and individual levels [1]. One specific trend based on digitalization is the use of *wearable devices* [2–5], also referred to as wearable technologies or wearables [6]. Today it is easy for end users to track and monitor physiological parameters such as heart rate in real time using such devices. Wearables can be described as advanced sensor and computing technologies [7] that are incorporated into different accessories including clothing, fashion accessories (e.g., watch, wristband), or other everyday items worn by consumers [8, 9] (for further examples of wearables devices, please see [6]). They continuously capture, collect and transmit physiological data, providing simple opportunities to improve the quality of life [10]. Indeed, the market research firm Gartner [11] reported recently that interest in health monitoring is growing. Specifically, consumer spending on smartwatches increased by 17.6% compared to 2019 and reached $21.8 billion in 2020. Gartner forecasts further growth in spending due to new processor technologies and improvements in solid-state batteries to increase battery life and shortened charging time, estimating spending of $31.4 billion in 2022. Besides the technical improvements, wearables also offer a wide range of applications. For example, they are equipped with many sensors such as accelerometers and gyroscopes [12] and can thereby even measure the vital signs of patients and specific health conditions (e.g., body and skin temperature, arterial blood pressure, heart rate, respiration rate) [13]. Consequently, wearables are becoming increasingly popular and experts predict that a growing percentage of the world's population will own at least one device [14].

However, there are several limitations that come along with the use of wearable devices. For example, Dunn et al. [15] argue that the accuracy of wearables must be established with large clinical and field trials. An inaccuracy of the measurement may lead individuals to under- or overestimate their level of physical activity or physiological activation, limiting effectiveness for lifestyle interventions. According to Piwek et al. [16], permanent lifestyle monitoring with inaccurate measurements via wearables could therefore cause confusion and anxiety. Interestingly, prior to purchase, consumers are typically informed in the footnote of product pages that the measurements are not intended for medical or related use. As an example, a note on the blood oxygen app measurements of the Apple Watch Series 6 indicates that it is "*not intended for medical use, including self-diagnosis or consultation with a doctor, and are only designed for general fitness and wellness purposes*" [17]. Especially for important indicators of an individual's physiological state, such as heart rate (HR) or heart rate variability (HRV), it is crucial to have accurate values. Thus, a fundamental question arises: *How reliable and valid are HR and HRV measurements based on wearable devices?*

Against the background of the importance of the consumer-centric view in digital health [18], we reviewed the scientific literature on HR and HRV. Specifically, we focused on the Neuro-Information-Systems (NeuroIS) literature. NeuroIS is a subfield within the Information Systems (IS) discipline that uses neuroscience and neurophysiological tools to develop knowledge related to the impact of information and communication technologies (ICT) [19, 20]. This interdisciplinary research discipline contributes to the explanation of users' cognitive and affective processes that explain why and how certain effects occur in the use of ICT [21] (for a description of the genesis of NeuroIS, please see Riedl and Léger [22], pp. 73–74).

According to Rouast et al. [23], especially HR as a measure, along with the related HRV measure, contributes to a deeper understanding of cognitive and affective processes in IS. This perspective is confirmed by seminal NeuroIS research agenda contributions (e.g., [24]). Hence, a review of the extant literature, along with a critical evaluation of the field, is crucial for the future development of this viable research field. Thus, the aim of this literature review is to provide a comprehensive overview of existing research using wearable devices to measure HR and HRV. Based on a systematic analysis of the NeuroIS literature published in peer-reviewed academic journals and conference proceedings, we address, in addition to the most fundamental question of reliability and validity, three further questions. The four research questions (RQs) addressed in this paper are:

- **RQ1: Who published HR and HRV research?** This analysis is particularly valuable in a highly interdisciplinary field, as it can identify reviewers and potential collaborators with relevant experience in HR and HRV research.
- **RQ2: What kind of HR and HRV research has been published?** This analysis provides insights for the future development of HR and HRV research.
- **RQ3: With which wearable devices was HR and HRV measured?** This analysis reveals methodological approaches and well-established devices in HR and HRV research.
- **RQ4: How reliable and valid are HR and HRV measurements based on wearable devices?** This analysis reveals the reliability and validity of measurements based on wearable devices used in HR and HRV contributions in the NeuroIS field.

The remainder of this paper is structured as follows: The following Section 2 outlines fundamentals of HR and its measurement. The knowledge presented in this section is abstracted and synthesizes major findings with the goal to provide a brief overview for the mainstream IS researcher (who is typically unfamiliar with the physiological basis of HR and HRV). Section 3 describes the research methodology of this literature review. Results are presented in Section 4. Finally, in Section 5, we make concluding remarks and address our implications for future IS research based on HR and HRV.

2 Heart Rate Fundamentals and Measurement

The heart supplies blood to the organs and tissues in the body: with each heartbeat, the heart muscle contracts and pumps oxygenated blood into the large vessels of the *circulatory system* – also referred to as cardiovascular system [25]. The heart pumps around 7,500 liters of blood per day and beats around 50-90 times per minute (resting state, exceptions exist) [26], which results in roughly 100,000 heartbeats per day [27]. The heart muscle is electrically activated by the heart's conduction system [28]. The electrical impulse for the heartbeat originates in the *sinoatrial node*, a structure located in the area of the junction of the right atrium and superior vena cava [28, 29]. The sinoatrial node consists of a collection of specialized muscle fibers (i.e., *myocytes*) with electrophysiological properties that are capable of spontaneously generating electrical impulses responsible for heart contraction [28, 30] (for more details about the conduction system and the cardiac development, please see [31]).

HR, like other bodily functions such as digestion, respiratory rate, pupillary response, urination, and sexual arousal, is regulated automatically and largely unconsciously by the *autonomic nervous system* (ANS) [32]. In general, ANS is a group of nerves and nerve cells which are responsible, among others, for the innervation of the blood vessels, the respiratory tract, the heart, the intestines and the urogenital organs [33]. It consists of the sympathetic division (which activates the body), the parasympathetic division (which relaxes the body) and the enteric nervous system (which governs the function of the gastrointestinal tract). From an IS perspective, both the *sympathetic nervous system* (SNS) and *parasympathetic nervous system* (PNS) are critical, while the enteric part is less relevant [22, 34]. SNS is activated in response to stress [32] and is responsible for “fight-or-flight” responses [22, 34, 35]. In contrast, PNS is responsible for energy building, food digestion, and assimilation, and serves to restore homeostasis, thereby contributing to relaxation and recovering [36]. Hence, it is the underlying structure of a “rest-and-digest” response [22, 34]. Importantly, HR is modulated on a beat-to-beat basis by the combined effects of the SNS and PNS nervous systems on the sinoatrial node [37].

SNS and PNS act in a finely tuned but opposing manner in the heart, as SNS has an activating effect (i.e., raises heartbeat) and PNS has an inhibiting effect (i.e., lowers heartbeat) [22, 34, 38, 39]. They enable the body to maintain stability in the face of constantly changing external conditions [40]. When we experience an emotion like stress, we breathe faster and heavier, muscles tension increases, palms get sweaty, HR increases, and blood pressure raises [40] (for further typical physiological responses of the SNS and PNS, please see Riedl and Léger [22, p. 42]). Therefore, among other physiological responses, HR can be used as an indicator of physiological state to measure autonomic nervous system activity [41, 42] and provides an objective measure of a person's ability to adapt to environmental demands [43]. Generally, HR corresponds to 60,000 divided by the time in milliseconds (ms) between adjacent heartbeats [44]. As an example, if the time between two consecutive heartbeats is 1 second (= 1,000 ms), HR is 60,000 / 1,000 = 60 beats per minute. HR can be affected by emotional stimuli. For example, stimuli with high valence (e.g., joy or happiness) can cause an increase in HR [45], whereas frightening stimuli can cause an increase or decrease in HR, depending on context and the specific content of a stimulus [45, 46]. Sheng and Joginapelly [42] indicate that HR tends to slow when a user is exposed to emotional stimuli, while the rate of slowing is usually higher with negative stimuli than with positive stimuli.

The analysis of changes in HR over time provides information about autonomic functioning – also referred to as heart rate variability, hereafter *HRV* [37, 44]. HRV is the measurement of the oscillation of the intervals between successive heartbeats [42], which is referred to as sinus RR intervals over time, hereafter *RR interval* [47]. To determine the instantaneous HR (i.e., *NN interval*), the RR intervals have to be adjusted for ectopic heartbeats caused by depolarizations of the sinoatrial node (e.g., heartbeat is too fast or too slow) [48]. This determination may be more variable and complex in healthy individuals compared with patients with congestive heart failure [49]. Referring to Stein and Pu [37], abnormal, usually decreased HRV is generally found in clinical conditions associated with autonomic dysfunction (e.g., congestive heart failure, diabetes, end-stage renal disease). HRV can also explain a substantial amount of individual variability in self-control over food intake, as individuals with higher HRV are better able to regulate cravings in the face of taste temptations [50]. However, stress-related disorders (e.g., triggered by enhanced negative emotions or dysregulation of physiological functions), including depression and anxiety, can affect the heart and its measurements. As an example, Yates [51] has shown that specific disorders (e.g., cardiovascular, neurological) come along with an increased HR and a decreased HRV. In this context, Patron et al. [41] found that poor emotion regulation (among others, a core symptom of depression) is associated with altered ANS function in terms of decreased HRV. Such a finding has many implications, and also important ones for IS research. As an example, it is important to understand computer users' mental workload during task execution to subsequently improve interface design of complex systems and the efficiency of human-computer interaction [52]. Mark et al. [53] used HR, among other indicators, to capture multidimensional biomarkers of workload in brain and body measurements. Against the background of the presented study results, which are meant to illustrate important knowledge on HR and HRV, it is critical that reliable and valid measurements are made with measurement devices, as even simple movements during measurement can significantly affect HR [54, 55]. In this context, Piwek et al. [16] tellingly write that without evidence of their accuracy, wearables "*will drift into obscurity*" (p. 6). In this paper, we shed light on critical measurement aspects in the HR and HRV domains, thereby contributing to the urgently need methodological discussions in the IS discipline in general and specifically in the NeuroIS field (e.g., [56, 57]).

3 Review Methodology

To identify HR and HRV contributions, we conducted a literature search and considered peer-reviewed journals and conference publications. The review process was based on existing recommendations for conducting literature searches [58–60]. This literature review comprises publications from January 2011 to 2021 (note that we included one online first contribution published in 2021 which appeared in the NeuroIS Retreat Proceedings; please see Hermes and Riedl [61]).

The starting point for our review was a recently published review by Riedl et al. [57], which investigated the development of the NeuroIS research field during the period 2008-2017, yielding 16 contributions on the measurement of HR. Thus, the keywords used for the present literature review were mainly derived from this original publication, as it provides both a broad introduction to the NeuroIS research field and its development. For our literature search, we used generic terms that represent the field (Nervous System, Neuro-Information-Systems, NeuroIS, Neuroscience) and terms representing the various methods of measuring HR and HRV highlighted in the publications (Chest Strap, Electrocardiogram, ECG, Heart, HR, HRV, Photoplethysmography, PPG). Our aim here was to verify the review by Riedl et al. [57] as well as to identify new contributions published since 2017. Outlets selected for our literature search process included all journals included in the Senior Scholars' Basket of the Association for Information Systems (AIS), as well as further academic journals and AIS conferences[1]. Outlets were mainly drawn from the business informatics (Wirtschaftsinformatik: WI) section of the third JOURQUAL (journal quality) ranking of the German Academic Association for Business Research, which also encompasses all outlets included in the Senior Scholars' Basket of the AIS and AIS conferences[2]. To increase the emphasis on specific NeuroIS contributions, we also searched for publications in the existing NeuroIS Retreat conference proceedings.

[1] https://aisnet.org (Accessed on August 9, 2021)
[2] https://vhbonline.org (Accessed on August 9, 2021)

In total, the literature base of our review comprises 38 articles, including 17 peer-reviewed journal papers and 21 peer-reviewed conference proceedings papers.

4 Review Results

In this section, we present the main findings of our literature review, guided by our four RQs. An overview of the content of each subsection related to our RQs and their corresponding metrics is provided in **Table 1**.

Table 1. Overview of Research Questions and Metrics

Research Question	Metrics
Who published HR and HRV research?	• Author names • Number of authors of each paper
What kind of HR and HRV research has been published?	• Contribution: empirical study completed, empirical study research-in-progress, methodological paper, conceptual paper, review
With which wearable devices was HR and HRV measured?	• Type of measurement method • Devices used for measurement
How reliable and valid are HR and HRV measurements based on wearable devices?	• Evidence of reliability and validity of the used devices

4.1 Who published HR and HRV research?

Based on the analysis of N = 38 HR and HRV publications, we identified 120 different authors. The average number of authors per publication is 3.9 and the maximum number of authors is 12. Specifically, we found the following results: out of the 38 contributions, 11 publications had 3 authors, 10 publications had 4 authors, 7 publications had 5 authors, 6 publications had 2 authors, 2 publications had 6 authors, and one publication had 7 and 12 authors. Another finding of our analysis is that out of the 120 different authors, 3 researchers (i.e., Marc T. P. Adam, Christof Weinhardt and René Riedl) authored at least 5 publications and together 42% of all publications. Indeed, 2 researchers (i.e., Adam and Weinhardt) authored 5 publications together. Furthermore, 14 researchers (~12%) published at least 2 papers and were involved in 30% of all publications (see **Figure 1**).

Figure 1 shows the concentration of HR and HRV publications across authors. The x-axis shows the cumulative percentage of authors, while the y-axis shows the cumulative percentage of contributions. Based on our dataset, we calculated the Gini coefficient (GC), a popular measure of inequality. GC is 0.19. A GC of 0 expresses perfect equality, where all authors would have contributed an equal number of publications to the HR and HRV literature. A GC of 1 expresses maximal inequality. It follows that there is not much inequality.

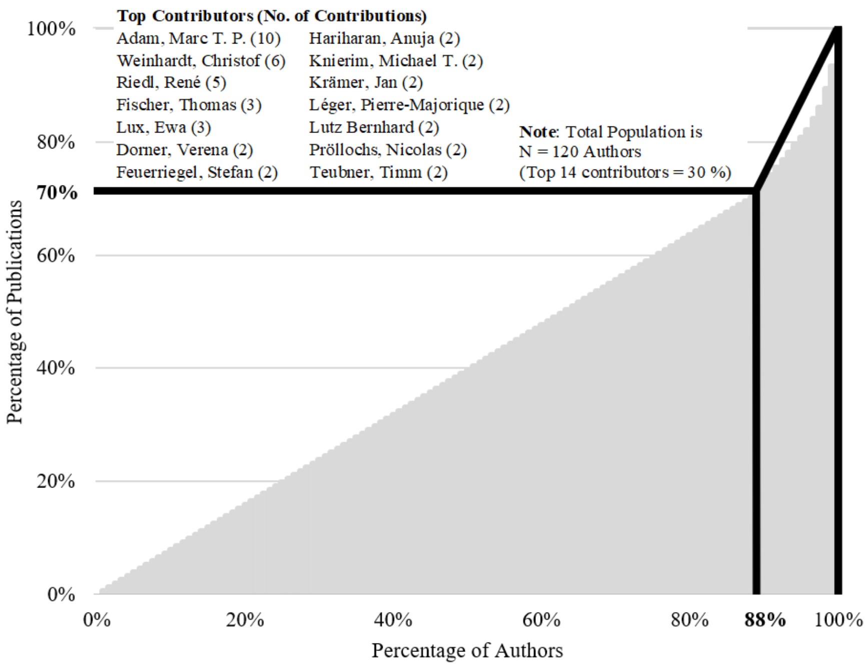

Figure 1. Concentration of HR and HRV Publications across Authors

4.2 What kind of HR and HRV research has been published?

This subsection classifies all 38 HR and HRV publications in terms of their contribution. For this purpose, we used 5 categories that have been successfully applied in recent similar publications (e.g., [57], [62]). A brief description of the categories follows before **Table 2** lists all 38 HR and HRV publications with their corresponding reference.

- **Empirical Study Completed**: The focus of these publications is on the empirical testing of the relationship between at least two variables, including information about the study design, measurement method and analysis procedures, and the results of the study.
- **Empirical Study Research-in-Progress**: These publications resemble completed empirical studies in that they typically present preliminary results or their study design without collecting or fully analyzing data.
- **Methodological Paper**: These publications describe new or existing tools as well as methodological approaches relevant to HR and HRV research (e.g., a non-contact PPG algorithm approach to measure HR [23]).
- **Conceptual Paper**: These publications discuss potential topics for HR and HRV research such as a real-time health-monitoring service by combining wearable devices and recommendation systems [63].

- **Review**: These publications focus on the analysis of previous research, based on a review of the literature. For example, Lux et al. [21] conducted a literature review on studies that examine self and foreign live biofeedback based on neurophysiological data for healthy subjects in an information systems context.

Table 2. Types of Contributions of HR and HRV Publications

Contribution Type	Reference(s)	Sum
Empirical Study Completed	[42, 44, 54, 64–83]	**23**
Empirical Study Research-in-Progress	[61, 84–92]	**10**
Methodological Paper	[23, 93]	**2**
Conceptual Paper	[63]	**1**
Review	[21, 94]	**2**

4.3 With which wearable devices was HR and HRV measured?

Based on the analysis of N = 38 HR and HRV publications, we identified 5 different methodological approaches to perform heart-related measurements. A brief description of the methodological approaches follows before **Table 3** lists all measurement types with the corresponding references. Publications that do not mention a (referenced) measurement type, such as reviews, are also included.

- **Electrocardiogram (ECG)**: ECG application usually involves placing a cathode electrode under the right clavicle, a ground electrode under the left clavicle, and an anode electrode on the left side of the abdomen. ECG sensors are a direct measurement of cardiac activity as they detect the electrical activity generated by a heartbeat in the chest area. ECG measurement is accurate at the ms level [22].
- **Chest Strap**: The chest strap is another option for ECG-based heartbeat measurement [95]. The electrical activity generated by a heartbeat is sent wirelessly from the sensor in the chest strap to a suitable receiver (e.g., wristwatch or other comparable receivers).
- **Photoplethysmography (PPG)**: PPG sensors use light-based technology to measure blood flow rate driven by the heart's pumping action (i.e., optical approach for measuring blood volume pulse). They usually measure blood properties at remote locations such as the wrist or finger. Therefore, high-frequency components of the signal are attenuated due to the long distance that blood must travel through the body before it is measured at the remote body sites. Thus, pulse wave velocity and the vascular path from the heart to the PPG sensor location, among other factors, can affect PPG-based measurement [62].
- **Non-Contact Pulse Rate Assessment Software**: The research by Lux et al. [89] aimed to investigate the effect of live group biofeedback on user behavior using participants' HR. The open-source software Eulerian Video Magnification (EVM) by Wu et al. [96] is used for cardiac measurement. EVM can visualize hidden information, such as a person's blood flow, by the algorithm performing spatial decomposition and subsequent temporal filtering of the respective video sequence. Among other things, this software can be applied to a video sequence in real-time.

- **Non-Contact PPG Algorithm Approach**: The algorithm proposed by Rouast et al. [23] leverages the slight variations in skin color that occur periodically with the user's pulse. This methodological approach would enable mobile HR measurements without interfering with the users' natural environment.

Table 3. Types of HR and HRV Measurement in Reviewed Publications

Measurement Type	Reference(s)	Sum
Electrocardiogram	[44, 66, 68–70, 73, 74, 76–78, 80–82, 85, 88, 92]	**16**
Chest Strap	[54, 61, 64, 72, 75, 79, 86, 87, 93]	**9**
Photoplethysmography	[42, 65, 67, 71, 83]	**5**
Non-Contact Pulse Rate Assessment Software	[89]	**1**
Non-Contact PPG Algorithm Approach	[23]	**1**
No (referenced) Measurement Type	[21, 63, 84, 90, 91, 94]	**6**

To get a sense of the various devices which have been used in HR and HRV research, **Table 4** shows details regarding the chest strap and PPG-based measurements. Apart from the publications in which no (referenced) measurement type was mentioned, these two measurement methods were used (completed studies) or are intended to be used (research-in-progress) in 46% of the studies. Specifically, we found the following results: Out of the 30 papers that performed heart-related measurements, 16 publications used an ECG (53%), 9 publications used a chest strap (30%), and 5 publications used a PPG sensor (16%). Another finding of our analysis is that out of the 9 publications that used a chest strap, the Polar H7 Heart Rate Sensor was used in most cases (see **Table 4**).

Table 4. Devices in HR and HRV Measurement in Reviewed Publications

Type	Device	Reference(s)
Chest Strap	Dry electrode chest strap	[79]
	Garmin ANT+ Heart Rate Monitor	[54]
	Polar H7 Heart Rate Sensor	[61, 64, 86, 87, 93]
	Polar RS800	[72]
	Zephyr™ BioHarness 3	[75]
PPG	iHealth Feel Blood Pressure Monitor (BP5)	[83]
	LightStone Biofeedback Finger Sensors	[42]
	Microsoft Band	[65]
	Scosche RHYTHM+™	[71]
	UFI BioLog™ (six-channel)	[67]

4.4 How reliable and valid are HR and HRV measurements based on wearable devices?

This subsection examines the PPG-based measurement devices as identified in the HR and HRV publications from the reliability and validity perspectives. To this end, we conducted another literature search to identify validation studies on the measurement properties of a specific device (search protocol available upon request). Afterwards, **Table 5** summarizes our results, which are described in detail below.

In general, PPG-based measurements are particularly susceptible to motion artifacts [54, 55], regardless of whether the device is a consumer device or a research device [97] (for examples of wearable devices for consumers, clinics, and research, please see Dunn et al. [15, p. 431]). Among others, the accuracy of such devices may depend on measurement site [55], applied pressure to the skin [98], ambient light [99], or various technological aspects of the light-based technology [100], including the use of red or green light, or the adopted PPG conditioning and processing [101], as well as the analysis of the reflected or transmitted light itself [102].

Of the 5 PPG-based measurement devices identified, only 1 device can be recommended based on current knowledge. Specifically, iHealth Feel Blood Pressure Monitor (BP5) has been successfully clinically evaluated for self/home measurement in adults [103] and for blood pressure measurement during pregnancy [104].

Regarding the LightStone biofeedback finger sensor, we did not find any relevant studies. In general, with this device, the user wears a sensor that measures HRV and skin conductance and navigates through a series of adventures on a video game-like interface. The aim is to achieve higher HRV through meditation skills and to gain better control over unconscious bodily processes. Users are encouraged to breathe deeply, and the games are stopped once users have developed a steady breathing cycle, resulting in increased HRV [105]. However, we could not find supporting evidence for reliability and/or validity and thus based on current knowledge we do neither recommend this wearable as consumer, nor as clinical or research device.

Regarding the three remaining devices (i.e., Microsoft Band, Scosche RHYTHM+™, UFI BioLog™), we cannot make a recommendation for use in IS research. Tophøj et al. [106] evaluated the reliability and validity of the Microsoft Band and concluded that it does not accurately count steps during lower speed walking. For this reason, it is especially unsuitable for patient groups who walk more slowly during rehabilitation; moreover, it is not appropriate for indoor walking counts either. As to Scosche RHYTHM+™, Parak and Korhonen [107] evaluated accuracy using values from a reference ECG signal. Reliability values for HR estimation compared to the reference were approximately 77% (used accuracy level <5%). Navalta et al. [108] came to a similar conclusion. They determined HR in trail running by evaluating chest strap values (i.e., Polar H7 with various wearable technology devices). Reliability was approximately 79% (used accuracy level <5%). Concerning the UFI BioLog™ we found research by Carpenter et al. [109] who evaluated monitors for vasomotor symptom assessment. They concluded that current versions of these monitors may not be suitable for outpatient clinical trials. Specifically, they pointed to the lack of consistency between self-reported physical activity and device-based measures of physical activity, such as HR measurement. Thus, due to lack of measurement accuracy, based on current knowledge we do not recommend these wearable devices, and this recommendation is independent from application context (consumer, clinical, or research).

Table 5. Devices in HR and HRV Measurement in Reviewed Publications and Use Recommendations based on Validation Studies for Consumer, Clinical, or Research Purposes

Device	Recommendation	Reference(s)
iHealth Feel Blood Pressure Monitor (BP5)	**Recommended**	[103, 104]
LightStone Biofeedback Finger Sensors	**Questionable**	[105]
Microsoft Band	**Not recommended**	[106]
Scosche RHYTHM+™	**Not recommended**	[107, 108]
UFI BioLog™ (six-channel)	**Not recommended**	[109]

5 Implications and Concluding Remarks

Manufacturers of wearable devices must be concerned about reliability and validity. Increasingly, such devices are used in the workplace to capture biomarkers of workload in brain and body measurements [53]. In the NeuroIS researchers' toolbox, wearable devices are of increasing relevance. First, wearables have a low degree of intrusiveness (i.e., the extent to which a measurement instrument interferes with an ongoing task) [56]. The degree of intrusiveness is low because they provide a high degree of movement freedom during (experimental) task execution, a high degree of natural position (can be used in sitting or walking situations), and a low degree of invasiveness (neither devices must be inserted into the body, nor must electrodes be attached to the body or scalp). Therefore, wearables can be used in an ideal way for human-computer interaction studies in both laboratory and field environments [56]. Regarding information retrieval [110], interested IS researchers may note that other methodological aspects of wearable devices and HR and HRV measurement are discussed in more detail in other publications such as biomedical engineering (e.g., IEEE Transactions on Biomedical Engineering, Physiological Measurement, Sensors), health information management (e.g., International Journal of Medical Informatics), or health informatics publications (e.g., JAMIA).

However, important indicators of an individual's physiological state, such as HR or HRV, could provide an index of ANS activity [41, 42] to objectively measure a person's ability to respond to environmental demands [43]. Indeed, Taelman et al. [39] indicate that stress triggers physiological processes in the human body. Thereby, stress-related disorders, for example triggered by enhanced negative emotions or dysregulation of physiological functions, lead to an increase in HR and a decrease in HRV [51]. An altered ANS functions (e.g., reduced HRV) constitutes a physiological correlate of depression [41]. In fact, stressors can activate specific cognitive and affective processes and underlying brain mechanisms [111]. The response towards stressors "*may also result in the activation of biological stress mechanisms that span a number of physiological systems*" [28, p. 21]. For example, work interruptions can lead to decreased psychological responsiveness to stress [112]. Apart from consequences on task performance (e.g., [113–116]), such interruptions can also lead to various negative psychological or performance-related outcomes (e.g., [117–119]). For this reason, wearables devices could be a potential early warning system to detect stress in the workplace in real time. More generally, designing stress-free workplaces in a digital world needs to be of high priority in economy and society because recent research shows that without appropriate measures, user stress can be significant (e.g., [120]). Especially because stress not only negatively affects the performance of companies, but also threatens the health of employees (e.g., [34]), this research domain holds great relevance in the future. However, an important precondition for use of such wearable devices in the workplace context, as well as in scientific research, is demonstration of reliability and validity of corresponding measurements.

Table 6 outlines our review results. We conclude that further efforts are needed to advance the use of wearables in both in the work settings and in scientific research.

Table 6. Overview of Implications for Research

Research Question	Implications
Who published HR and HRV research?	Research on HR and HRV is still relatively scarce. Our results show that there is a relatively small group of active authors (see **Figure 1**). The small absolute number of highly engaged researchers can be seen critical, yet a high level of inequality is not observed.
What kind of HR and HRV research has been published?	The field of HR and HRV research is still in a relatively nascent stage. As evidence for this conclusion, we identified only two methodological and one conceptual contribution (see **Table 2**). Our results indicate that that in the analysis period 2011-2021, there was no year in which more than seven papers were published.
With which wearable devices was HR and HRV measured?	Our review indicates that HR and HRV are predominantly investigated with ECG. However, there are already contributions in which measurements are made with a chest strap or with PPG sensors (see **Table 3** and **Table 4**). We suspect that technological advances will create even more opportunities for researchers in this research field and expect a rising number of additional publications in the coming years based on wearable devices.
How reliable and valid are HR and HRV measurements based on wearable devices?	Wearable devices can measure HR and HRV in a reliable and valid way. Based on the little current evidence in most cases both reliability and validity of measurements are doubtful (see **Table 5**). For wearables to be used in both commercial and academic settings, further theoretical and methodological contributions are needed.

6 Acknowledgements

This research was funded by the Austrian Science Fund (FWF) as part of the project "Technostress in Organizations" (project number: P 30865) at the University of Applied Sciences Upper Austria.

References

1. Gray, J., Rumpe, B.: Models for digitalization. Softw. Syst. Model. 14, 1319–1320 (2015)
2. Bardhan, I., Chen, H., Karahanna, E.: Connecting systems, data, and people: A multidisciplinary research roadmap for chronic disease management. MIS Q. 44, 185–200 (2020)
3. Maltseva, K.: Wearables in the workplace: The brave new world of employee engagement. Bus. Horiz. 63, 493–505 (2020)
4. Reid, R.C., Mahbub, I.: Wearable self-powered biosensors. Curr. Opin. Electrochem. 19, 55–62 (2020)
5. Qaim, W. Bin, Ometov, A., Molinaro, A., Lener, I., Campolo, C., Lohan, E.S., Nurmi, J.: Towards energy efficiency in the internet of wearable things: A systematic review. IEEE Access. 8, 175412–175435 (2020)
6. Kalantari, M.: Consumers adoption of wearable technologies: Literature review, synthesis, and future research agenda. Int. J. Technol. Mark. 12, 274–307 (2017)
7. Jacobs, J. V., Hettinger, L.J., Huang, Y.-H., Jeffries, S., Lesch, M.F., Simmons, L.A., Verma, S.K., Willetts, J.L.: Employee acceptance of wearable technology in the workplace. Appl. Ergon. 78, 148–156 (2019)
8. Ferreira, J.J., Fernandes, C.I., Rammal, H.G., Veiga, P.M.: Wearable technology and consumer interaction: A systematic review and research agenda. Comput. Human Behav. 118, 106710 (2021)
9. Nanjappan, V., Liang, H.-N., Wang, W., Man, K.L.: Big data: A classification of acquisition and generation methods. In: Hsu, H.-H., Chang, C.-Y., and Hsu, C.-H. (eds.) Big Data Analytics for Sensor-Network Collected Intelligence: A volume in Intelligent Data-Centric Systems. pp. 3–20. Elsevier, London (2017)
10. Seneviratne, S., Hu, Y., Nguyen, T., Lan, G., Khalifa, S., Thilakarathna, K., Hassan, M., Seneviratne, A.: A survey of wearable devices and challenges. IEEE Commun. Surv. Tutorials. 19, 2573–2620 (2017)
11. Gartner: Gartner forecasts global spending on wearable devices to total $81.5 billion in 2021, https://www.gartner.com/en/newsroom/press-releases/2021-01-11-gartner-forecasts-global-spending-on-wearable-devices-to-total-81-5-billion-in-2021 (Accessed on August 13, 2021)
12. Williamson, J., Liu, Q., Lu, F., Mohrman, W., Li, K., Dick, R., Shang, L.: Data sensing and analysis: Challenges for wearables. In: The 20th Asia and South Pacific Design Automation Conference. pp. 136–141. IEEE, Chiba (2015)
13. Isravel, D.P., Arulkumar, D., Raimond, K., Issac, B.: A novel framework for quality care in assisting chronically impaired patients with ubiquitous computing and ambient intelligence technologies. In: Peter, J.D. and Fernandes, S.L. (eds.) Systems Simulation and Modeling for Cloud Computing and Big Data Applications: A volume in Advances in ubiquitous sensing applications for healthcare. pp. 61–79. Elsevier, London (2020)
14. Mertz, L.: Are wearables safe?: We carry our smart devices with us everywhere - even to bed - but have we been sleeping with the enemy, or are cautionary tales overinflated? IEEE Pulse. 7, 39–43 (2016)

15. Dunn, J., Runge, R., Snyder, M.: Wearables and the medical revolution. Per. Med. 15, 429–448 (2018)
16. Piwek, L., Ellis, D.A., Andrews, S., Joinson, A.: The rise of consumer health wearables: Promises and barriers. PLOS Med. 13, e1001953 (2016)
17. Apple Inc.: Apple Watch Series 6, https://www.apple.com/apple-watch-series-6/ (Accessed on August 13, 2021)
18. Agarwal, R., Dugas, M., Gao, G. (Gordon), Kannan, P.K.: Emerging technologies and analytics for a new era of value-centered marketing in healthcare. J. Acad. Mark. Sci. 48, 9–23 (2020)
19. Riedl, R., Banker, R.D., Benbasat, I., Davis, F.D., Dennis, A.R., Dimoka, A., Gefen, D., Gupta, A., Ischebeck, A., Kenning, P.H., Müller-Putz, G.R., Pavlou, P.A., Straub, D.W., vom Brocke, J., Weber, B.: On the foundations of NeuroIS: Reflections on the Gmunden Retreat 2009. Commun. Assoc. Inf. Syst. 27, 243–264 (2010)
20. Riedl, R., Davis, F.D., Banker, R.D., Kenning, P.H.: Neuroscience in information systems research: Applying knowledge of brain functionality without neuroscience tools. Springer, Cham (2017)
21. Lux, E., Adam, M.T.P., Dorner, V., Helming, S., Knierim, M.T., Weinhardt, C.: Live biofeedback as a user interface design element: A review of the literature. Commun. Assoc. Inf. Syst. 43, 257–296 (2018)
22. Riedl, R., Léger, P.-M.: Fundamentals of NeuroIS: Information systems and the brain. Springer, Berlin Heidelberg (2016)
23. Rouast, P. V., Adam, M.T.P., Cornforth, D.J., Lux, E., Weinhardt, C.: Using contactless heart rate measurements for real-time assessment of affective states. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2016. LNISO, vol. 16, pp. 157–163. Springer, Cham (2017)
24. Dimoka, A., Davis, F.D., Gupta, A., Pavlou, P.A., Banker, R.D., Dennis, A.R., Ischebeck, A., Müller-Putz, G.R., Benbasat, I., Gefen, D., Kenning, P.H., Riedl, R., vom Brocke, J., Weber, B.: On the use of neurophysiological tools in IS research: Developing a research agenda for NeuroIS. MIS Q. 36, 679–702 (2012)
25. Peate, I.: Anatomy and physiology, 8. The circulatory system. Br. J. Healthc. Assist. 12, 62–67 (2018)
26. Nanchen, D.: Resting heart rate: What is normal? Heart. 104, 1048–1049 (2018)
27. Peate, I.: The heart: An amazing organ. Br. J. Healthc. Assist. 15, 72–77 (2021)
28. Madani, M.M., Golts, E.: Cardiovascular anatomy. In: Reference Module in Biomedical Sciences. Elsevier (2014)
29. Olshansky, B., Chung, M.K., Pogwizd, S.M., Goldschlager, N.: Sinus node: Normal and abnormal rhythms. In: Olshansky, B., Chung, M.K., Pogwizd, S.M., and Goldschlager, N. (eds.) Arrhythmia Essentials. 2nd Edition, pp. 1–27. Elsevier, Philadelphia (2017)
30. Severs, N.J.: Constituent cells of the heart and isolated cell models in cardiovascular research. In: Piper, H.M. and Isenberg, G. (eds.) Isolated Adult Cardiomyocytes: Structure and Metabolism. pp. 3–41. CRC Press, Boca Raton (2019)
31. Moorman, A.F.M., de Jong, F., Denyn, M.M.F.J., Lamers, W.H.: Development of the cardiac conduction system. Circ. Res. 82, 629–644 (1998)

32. Jänig, W.: Autonomic nervous system. In: Schmidt, R.F. and Thews, G. (eds.) Human Physiology. 2nd Edition, pp. 333–370. Springer, Berlin Heidelberg (1989)
33. Gabella, G.: Autonomic nervous system. In: eLS. Wiley, Chichester (2012)
34. Riedl, R.: On the biology of technostress: Literature review and research agenda. ACM SIGMIS Database DATABASE Adv. Inf. Syst. 44, 18–55 (2013)
35. Noyes, F.R., Barber-Westin, S.D.: Diagnosis and treatment of complex regional pain syndrome. In: Noyes, F.R. (ed.) Noyes' knee disorders: Surgery, rehabilitation, clinical outcomes. 2nd Edition, pp. 1122–1160. Elsevier, Philadelphia (2017)
36. Fritz, S., Chaitow, L., Hymel, G.M.: Review of pertinent anatomy and physiology. In: Fritz, S., Chaitow, L., and Hyme, G.M. (eds.) Clinical Massage in the Healthcare Setting. pp. 140–195. Elsevier, St. Louis (2008)
37. Stein, P.K., Pu, Y.: Heart rate variability, sleep and sleep disorders. Sleep Med. Rev. 16, 47–66 (2012)
38. Florea, V.G., Cohn, J.N.: The autonomic nervous system and heart failure. Circ. Res. 114, 1815–1826 (2014)
39. Taelman, J., Vandeput, S., Spaepen, A., Van Huffel, S.: Influence of mental stress on heart rate and heart rate variability. In: Sloten, J. van der, Verdonck, P., Nyssen, M., and Haueisen, J. (eds.) 4th European Conference of the International Federation for Medical and Biological Engineering: ECIFMBE 2008 23–27 November 2008 Antwerp, Belgium. IFMBE, vol. 22, pp. 1366–1369. Springer, Berlin Heidelberg (2009)
40. Djurica, D., Mendling, J.: The influence of negative emotion as affective state on conceptual models comprehension. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2020. LNISO, vol. 43, pp. 145–152. Springer, Cham (2020)
41. Patron, E., Messerotti Benvenuti, S., Favretto, G., Gasparotto, R., Palomba, D.: Depression and reduced heart rate variability after cardiac surgery: The mediating role of emotion regulation. Auton. Neurosci. 180, 53–58 (2014)
42. Sheng, H., Joginapelly, T.: Effects of web atmospheric cues on users' emotional responses in e-commerce. AIS Trans. Human-Computer Interact. 4, 1–24 (2012)
43. Francis, H.M., Penglis, K.M., McDonald, S.: Manipulation of heart rate variability can modify response to anger-inducing stimuli. Soc. Neurosci. 11, 545–552 (2016)
44. Léger, P.-M., Davis, F.D., Cronan, T.P., Perret, J.: Neurophysiological correlates of cognitive absorption in an enactive training context. Comput. Human Behav. 34, 273–283 (2014)
45. Kreibig, S.D.: Autonomic nervous system activity in emotion: A review. Biol. Psychol. 84, 394–421 (2010)
46. Löw, A., Lang, P.J., Smith, J.C., Bradley, M.M.: Both predator and prey: Emotional arousal in threat and reward. Psychol. Sci. 19, 865–873 (2008)
47. Cowan, M.J.: Measurement of heart rate variability. West. J. Nurs. Res. 17, 32–48 (1995)
48. Malik, M., Bigger, J.T., Camm, A.J., Kleiger, R.E., Malliani, A., Moss, A.J., Schwartz, P.J.: Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Eur. Heart J. 17, 354–381 (1996)

49. Cysarz, D., Lange, S., Matthiessen, P.F., Leeuwen, P. van: Regular heartbeat dynamics are associated with cardiac health. Am. J. Physiol. Integr. Comp. Physiol. 292, R368–R372 (2007)
50. Maier, S.U., Hare, T.A.: Higher heart-rate variability is associated with ventromedial prefrontal cortex activity and increased resistance to temptation in dietary self-control challenges. J. Neurosci. 37, 446–455 (2017)
51. Yates, D.: Heightening the threat. Nat. Rev. Neurosci. 22, 4–5 (2021)
52. Ayaz, H., Shewokis, P.A., Bunce, S., Izzetoglu, K., Willems, B., Onaral, B.: Optical brain monitoring for operator training and mental workload assessment. Neuroimage. 59, 36–47 (2012)
53. Mark, J., Curtin, A., Kraft, A., Sargent, A., Perez, A., Friedman, L., Barkan, A., Sands, T., Casebeer, W., Ziegler, M., Ayaz, H.: Multimodal cognitive workload assessment using EEG, fNIRS, ECG, EOG, PPG, and eye-tracking. Front. Hum. Neurosci. 12, (2018)
54. Konok, V., Pogány, Á., Miklósi, Á.: Mobile attachment: Separation from the mobile phone induces physiological and behavioural stress and attentional bias to separation-related stimuli. Comput. Human Behav. 71, 228–239 (2017)
55. Maeda, Y., Sekine, M., Tamura, T.: Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography. J. Med. Syst. 35, 969–976 (2011)
56. Riedl, R., Davis, F.D., Hevner, A.R.: Towards a NeuroIS research methodology: Intensifying the discussion on methods, tools, and measurement. J. Assoc. Inf. Syst. 15, I–XXXV (2014)
57. Riedl, R., Fischer, T., Léger, P.-M., Davis, F.D.: A decade of NeuroIS research: Progress, challenges, and future directions. ACM SIGMIS Database DATABASE Adv. Inf. Syst. 51, 13–54 (2020)
58. Webster, J., Watson, R.T.: Analyzing the past to prepare for the future: Writing a literature review. MIS Q. 26, xiii–xxiii (2002)
59. Kitchenham, B., Charters, S.: Guidelines for performing systematic literature reviews in software engineering version 2.3. EBSE Technical Report EBSE-2007-01, Keele University and University of Durham (2007)
60. vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A.: Reconstructing the giant: On the importance of rigour in documenting the literature search process. In: Newell, S., Whitley, E.A., Pouloudi, N., Wareham, J., and Mathiassen, L. (eds.) 17th European Conference on Information Systems (2009)
61. Hermes, A., Riedl, R.: Exploring the influence of personality traits on affective customer experiences in retailing: Combination of heart rate variability (HRV) and self-report measures. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Müller-Putz, G.R. (eds.) NeuroIS Retreat 2021. pp. 29–38. http://www.neurois.org/wp-content/uploads/2021/09/NeuroIS-Retreat-2021-Preprint-Proceedings.pdf (2021)
62. Weber, B., Fischer, T., Riedl, R.: Brain and autonomic nervous system activity measurement in software engineering: A systematic literature review. J. Syst. Softw. 178, 110946 (2021)

63. Roy, S.N., Srivastava, S.K., Gururajan, R.: Integrating wearable devices and recommendation system: Towards a next generation healthcare service delivery. J. Inf. Technol. Theory Appl. 19, 4–31 (2018)
64. Fischer, T., Riedl, R.: Technostress measurement in the field: A case report. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2020. LNISO, vol. 43, pp. 71–78. Springer, Cham (2020)
65. Gaskin, J., Jenkins, J., Meservy, T., Steffen, J., Payne, K.: Using wearable devices for non-invasive, inexpensive physiological data collection. In: Hawaii International Conference on System Sciences. pp. 597–605 (2017)
66. Hariharan, A., Dorner, V., Adam, M.T.P.: Impact of cognitive workload and emotional arousal on performance in cooperative and competitive interactions. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2016. LNISO, vol. 16, pp. 35–42. Springer, Cham (2017)
67. Jensen, M., Piercy, C., Elzondo, J., Twyman, N., Valacich, J., Miller, C., Lee, Y.-H., Dunbar, N., Bessarabova, E., Burgoon, J., Adame, B., Wilson, S.: Exploring failure and engagement in a complex digital training game: A multi-method examination. AIS Trans. Human-Computer Interact. 8, 1–20 (2016)
68. Kothgassner, O.D., Felnhofer, A., Hlavacs, H., Beutl, L., Palme, R., Kryspin-Exner, I., Glenk, L.M.: Salivary cortisol and cardiovascular reactivity to a public speaking task in a virtual and real-life environment. Comput. Human Behav. 62, 124–135 (2016)
69. Lutz, B., Adam, M.T.P., Feuerriegel, S., Pröllochs, N., Neumann, D.: Affective information processing of fake news: Evidence from NeuroIS. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2019. LNISO, vol. 32, pp. 121–128. Springer, Cham (2020)
70. Lutz, B., Adam, M.T.P., Feuerriegel, S., Pröllochs, N., Neumann, D.: Identifying linguistic cues of fake news associated with cognitive and affective processing: Evidence from NeuroIS. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2020. LNISO, vol. 43, pp. 16–23. Springer, Cham (2020)
71. Öksüz, N., Biswas, R., Shcherbatyi, I., Maass, W.: Measuring biosignals of overweight and obese children for real-time feedback and predicting performance. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2017. LNISO, vol. 25, pp. 185–193. Springer, Cham (2018)
72. Ortiz de Guinea, A., Webster, J.: An investigation of information systems use patterns: Technological events as triggers, the effect of time, and consequences for performance. MIS Q. 37, 1165–1188 (2013)
73. Shalom, J.G., Israeli, H., Markovitzky, O., Lipsitz, J.D.: Social anxiety and physiological arousal during computer mediated vs. face to face communication. Comput. Human Behav. 44, 202–208 (2015)

74. Teubner, T., Adam, M.T.P., Riordan, R.: The impact of computerized agents on immediate emotions, overall arousal and bidding behavior in electronic auctions. J. Assoc. Inf. Syst. 16, 838–879 (2015)
75. Tozman, T., Magdas, E.S., MacDougall, H.G., Vollmeyer, R.: Understanding the psychophysiology of flow: A driving simulator experiment to investigate the relationship between flow and heart rate variability. Comput. Human Behav. 52, 408–418 (2015)
76. Walla, P., Lozovic, S.: The effect of technology on human social perception: A multi-methods NeuroIS pilot investigation. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2019. LNISO, vol. 32, pp. 63–71. Springer, Cham (2020)
77. Adam, M.T.P., Gamer, M., Krämer, J., Weinhardt, C.: Measuring emotions in electronic markets. In: International Conference on Information Systems (2011)
78. Adam, M.T.P., Krämer, J., Weinhardt, C.: Excitement up! Price down! Measuring emotions in Dutch auctions. Int. J. Electron. Commer. 17, 7–40 (2012)
79. Astor, P.J., Adam, M.T.P., Jerčić, P., Schaaff, K., Weinhardt, C.: Integrating biosignals into information systems: A NeuroIS tool for improving emotion regulation. J. Manag. Inf. Syst. 30, 247–278 (2013)
80. Barral, O., Kosunen, I., Jacucci, G.: No need to laugh out loud: Predicting humor appraisal of comic strips based on physiological signals in a realistic environment. ACM Trans. Comput. Interact. 24, 1–29 (2018)
81. Buettner, R., Bachus, L., Konzmann, L., Prohaska, S.: Asking both the user's heart and its owner: Empirical evidence for substance dualism. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2018. LNISO, vol. 29, pp. 251–257. Springer, Cham (2019)
82. Cipresso, P., Serino, S., Gaggioli, A., Albani, G., Mauro, A., Riva, G.: Psychometric modeling of the pervasive use of Facebook through psychophysiological measures: Stress or optimal experience? Comput. Human Behav. 49, 576–587 (2015)
83. Clayton, R.B., Leshner, G., Almond, A.: The extended iSelf: The impact of iPhone separation on cognition, emotion, and physiology. J. Comput. Commun. 20, 119–135 (2015)
84. Fallon, M., Spohrer, K., Heinzl, A.: Wearable devices: A physiological and self-regulatory intervention for increasing attention in the workplace. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2018. LNISO, vol. 29, pp. 229–238. Springer, Cham (2019)
85. Friemel, C., Morana, S., Pfeiffer, J., Maedche, A.: On the role of users' cognitive-affective states for user assistance invocation. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2017. LNISO, vol. 25, pp. 37–46. Springer, Cham (2018)

86. Jahn, K., Kordyaka, B., Ressing, C., Roeding, K., Niehaves, B.: Designing self-presence in immersive virtual reality to improve cognitive performance—A research proposal. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2019. LNISO, vol. 32, pp. 83–91. Springer, Cham (2020)
87. Kalischko, T., Fischer, T., Riedl, R.: Techno-unreliability: A pilot study in the field. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2019. LNISO, vol. 32, pp. 137–145. Springer, Cham (2020)
88. Knierim, M.T., Rissler, R., Hariharan, A., Nadj, M., Weinhardt, C.: Exploring flow psychophysiology in knowledge work. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2018. LNISO, vol. 29, pp. 239–249. Springer, Cham (2019)
89. Lux, E., Hawlitschek, F., Teubner, T., Niemeyer, C., Adam, M.T.P.: A hot topic—Group affect live biofeedback for participation platforms. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2015. LNISO, vol. 10, pp. 35–42. Springer, Cham (2015)
90. Seeber, I., Weber, B., Maier, R., de Vreede, G.-J.: The choice is yours: The role of cognitive processes for IT-supported idea selection. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: Gmunden Retreat on NeuroIS 2017. LNISO, vol. 25, pp. 17–24. Springer, Cham (2018)
91. Sharma, M., Biros, D.: Building trust in wearables for health behavior. J. Midwest Assoc. Inf. Syst. 2, 35–44 (2019)
92. Vasseur, A., Léger, P.-M., Sénécal, S.: The impact of symmetric web-design: A pilot study. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., Randolph, A.B., and Fischer, T. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2019. LNISO, vol. 32, pp. 173–180. Springer, Cham (2020)
93. Baumgartner, D., Fischer, T., Riedl, R., Dreiseitl, S.: Analysis of heart rate variability (HRV) feature robustness for measuring technostress. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2018. LNISO, vol. 29, pp. 221–228. Springer, Cham (2019)
94. Vogel, J., Auinger, A., Riedl, R.: Cardiovascular, neurophysiological, and biochemical stress indicators: A short review for information systems researchers. In: Davis, F.D., Riedl, R., vom Brocke, J., Léger, P.-M., and Randolph, A.B. (eds.) Information Systems and Neuroscience: NeuroIS Retreat 2018. LNISO, vol. 29, pp. 259–273. Springer, Cham (2019)
95. Sartor, F., Gelissen, J., van Dinther, R., Roovers, D., Papini, G.B., Coppola, G.: Wrist-worn optical and chest strap heart rate comparison in a heterogeneous sample of healthy individuals and in coronary artery disease patients. BMC Sports Sci. Med. Rehabil. 10, 10 (2018)

96. Wu, H.-Y., Rubinstein, M., Shih, E., Guttag, J., Durand, F., Freeman, W.: Eulerian video magnification for revealing subtle changes in the world. ACM Trans. Graph. 31, 1–8 (2012)
97. Reali, P., Tacchino, G., Rocco, G., Cerutti, S., Bianchi, A.M.: Heart rate variability from wearables: A comparative analysis among standard ECG, a smart shirt and a wristband. In: Blobel, B. and Giacomini, M. (eds.) pHealth 2019: Proceedings of the 16th International Conference on Wearable Micro and Nano Technologies for Personalized Health. pp. 128–133. IOS Press, Amsterdam (2019)
98. Taji, B., Chan, A.D.C., Shirmohammadi, S.: Effect of pressure on skin-electrode impedance in wearable biomedical measurement devices. IEEE Trans. Instrum. Meas. 67, 1900–1912 (2018)
99. Akinwande, D., Kireev, D.: Wearable graphene sensors use ambient light to monitor health. Nature. 576, 220–221 (2019)
100. Moço, A. V., Stuijk, S., de Haan, G.: New insights into the origin of remote PPG signals in visible light and infrared. Sci. Rep. 8, 8501 (2018)
101. Allen, J.: Photoplethysmography and its application in clinical physiological measurement. Physiol. Meas. 28, R1–R39 (2007)
102. Fallow, B.A., Tarumi, T., Tanaka, H.: Influence of skin type and wavelength on light wave reflectance. J. Clin. Monit. Comput. 27, 313–317 (2013)
103. Shang, F., Zhu, Y., Zhu, Z., Liu, L., Wan, Y.: Validation of the iHealth BP5 wireless upper arm blood pressure monitor for self-measurement according to the European Society of Hypertension International Protocol revision 2010. Blood Press. Monit. 18, 278–281 (2013)
104. Hofstede, A., Wollaars, H., van Drongelen, J.: A clinical evaluation of blood pressure measurement by iHealth BP5 in pregnancy. Pregnancy Hypertens. 17, 69–74 (2019)
105. Mason, E.B., Burkhart, K., Lazebnik, R.: Adolescent stress management in a primary care clinic. J. Pediatr. Heal. Care. 33, 178–185 (2019)
106. Tophøj, K.H., Petersen, M.G., Sæbye, C., Baad-Hansen, T., Wagner, S.: Validity and reliability evaluation of four commercial activity trackers' step counting performance. Telemed. e-Health. 24, 669–677 (2018)
107. Parak, J., Korhonen, I.: Evaluation of wearable consumer heart rate monitors based on photopletysmography. In: 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. pp. 3670–3673. IEEE, Chicago (2014)
108. Navalta, J.W., Montes, J., Bodell, N.G., Salatto, R.W., Manning, J.W., DeBeliso, M.: Concurrent heart rate validity of wearable technology devices during trail running. PLoS One. 15, e0238569 (2020)
109. Carpenter, J.S., Newton, K.M., Sternfeld, B., Joffe, H., Reed, S.D., Ensrud, K.E., Milata, J.L.: Laboratory and ambulatory evaluation of vasomotor symptom monitors from the menopause strategies finding lasting answers for symptoms and health network. Menopause. 19, 664–671 (2012)
110. Manning, C.D., Raghavan, P., Schütze, H.: Introduction to information retrieval. Cambridge University Press, New York (2008)
111. Riedl, R., Kindermann, H., Auinger, A., Javor, A.: Technostress from a neurobiological perspective: System breakdown increases the stress hormone cortisol in computer users. Bus. Inf. Syst. Eng. 4, 61–69 (2012)

112. Kerr, J.I., Naegelin, M., Weibel, R.P., Ferrario, A., La Marca, R., von Wangenheim, F., Hoelscher, C., Schinazi, V.R.: The effects of acute work stress and appraisal on psychobiological stress responses in a group office environment. Psychoneuroendocrinology. 121, 104837 (2020)
113. Basoglu, K.A., Fuller, M.A., Sweeney, J.T.: Investigating the effects of computer mediated interruptions: An analysis of task characteristics and interruption frequency on financial performance. Int. J. Account. Inf. Syst. 10, 177–189 (2009)
114. Gillie, T., Broadbent, D.: What makes interruptions disruptive? A study of length, similarity, and complexity. Psychol. Res. 50, 243–250 (1989)
115. Gluck, J., Bunt, A., McGrenere, J.: Matching attentional draw with utility in interruption. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. pp. 41–50. ACM Press, New York (2007)
116. Kapista, M., Blinnikova, I.: Task performance under the influence of interruptions. In: Hockey, G.R.J., Gaillard, A.W.K., and Burov, O. (eds.) Operator Functional State: The Assessment and Prediction of Human Performance Degradation in Complex Tasks. NATO Science Series, vol. 355, pp. 323–329. IOS Press, Amsterdam (2003)
117. Adamczyk, P.D., Bailey, B.P.: If not now, when? The effects of interruption at different moments within task execution. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. pp. 271–278. ACM Press, New York (2004)
118. Bailey, B.P., Konstan, J.A.: On the need for attention-aware systems: Measuring effects of interruption on task performance, error rate, and affective state. Comput. Human Behav. 22, 685–708 (2006)
119. Dodhia, R.M., Dismukes, R.K.: Interruptions create prospective memory tasks. Appl. Cogn. Psychol. 23, 73–89 (2009)
120. Fischer, T., Riedl, R.: Technostress research: A nurturing ground for measurement pluralism? Commun. Assoc. Inf. Syst. 40, 375–401 (2017)