Wearables and Lifestyle

Wearables and Stress

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List of Abbreviations

HRV – Heart Rate Variability

SC – Skin Conductance

RMSSD – root means square of successive differences

SCL - Skin Conductance Level

SCR - Skin Conductance Response

EDA – Electrodermal activity

HR – Heart rate

WASO - Wakefulness after sleep onset

SToA – State of The Art

Abstract

Wearables are becoming increasingly popular and highly accessible with their developers and producers coming up with more and more functionalities, many of which are related to bodily functions. Some of these bodily functions (heart rate variability, skin conductance, sleep) have been proven scientifically to indicate stress. Since mental stress is one thing scientists and media have drawn attention to lately, it is intriguing to explore how wearables could be used to gather data of known stress indicators. The current research project investigates how self-reported mental stress and self-reported satisfaction with sleep can be related to RMSSD and sleep metrics, measured with a Fitbit Sense wearable. Results show that more in-depth knowledge is needed about wearables' functionality, that to understand sleep quality and mental stress people (users) should be more involved in the process and that RMSSD shows promising potential to be used for integration with mental stress.

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Chapter 1 – Introduction

In recent times, countries, companies, universities, schools and individuals have started putting a lot of emphasis not only on people's physical health but also their mental such. The World Health Organization has expressed its concerns and recommendations in terms of mental health, stress and their connection to a healthy workplace environment [7]. Countries have started implementing rules and regulations to ensure that the companies and universities operating on their territory are taking sufficient measures to provide their employees and/or students with a healthy work/study environment (for example the Australian government released a fact sheet that states that "The Government will support employers, industries, small businesses and sole traders to create mentally healthy workplaces" [8]). On their turn companies and universities have made their own initiatives to help with that. For example, Amazon warehouses, which have been exposed by Frontline [1], as places having a highly stressful work environment have started implementing booths (called Amazen [2]) that help workers focus on mindfulness, thus reducing stress levels. An example from universities across the Netherlands is a stress booth (Mindfulnest [3]), which in the case of University of Twente, is situated at the entrance of the busiest study space – the Vrijhof library, which works all week long. This enclosed soundproof space is there for students that need to take a break from studying and concentrate on their thoughts. It is also evident, from the fact that one of the key pillars in the fourth industrial revolution (better known as Industry 4.0) is Society and People, that the world has started orientating towards beliefs which put people and their wellbeing in the centre of attention. There have been more and more appearances of psychologists and mental health specialists on TV and social media trying to help people manage and understand their levels of stress. In other words, they are trying to teach people emotional intelligence ("Perceptiveness and skill in dealing with emotions and interpersonal relationships", as defined by Oxford Dictionary [4]). While there are various measures of emotional intelligence, such as the Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT) [5] and the Emotional Quotient Inventory (EQ-I 2.0) [6], these tests have their limitations and are not universally accepted as definitive measures of emotional intelligence. In general, people have a hard time grasping such concepts by themselves. Understanding the world around them is easier than understanding what is happening "inside" of them. There are many people that overwork themselves simply because they do not understand how mentally stressed they are. Workplace stress is associated with physical disorders such as heart disease, hypoadrenia, immunosuppression, and chronic pain [9]. In terms of psychological effects workplace stress is believed to have an impact on depression, persistent anxiety, pessimism, and resentment [9]. To expand on that, stress and its accumulating presence can lead to increases in smoking, substance use, accidents, sleep problems, eating disorders, immunity suppression, exacerbations of autoimmune disease and other conditions in which excessive inflammation is a central feature, such as Coronary Heart Disease [10].

Giving people an opportunity to track their stress levels on a daily basis will allow them to be more aware of their personal circumstances and most probably account for them. This can be done via the help of wearables.

As discussed previously, people have a hard time understanding their emotional state. A self-reported type of approach to estimate people's stress levels does not seem like a good solution. People's bodies, on the other hand, have various mechanisms for coping with stressors. Even though, the response of the body is not immediately visible it can be measured through various indicators. Situations and environments change constantly so measurements should be taken on a regular basis, if not always. As such, measuring in laboratories would not be a good solution since it will take a lot of time, but also because circumstances change too often in everyday life and it is impossible to account for this unpredictability. On the other hand, wearable technologies are developing at a rapid pace to be able to measure more parameters, more often and in less obtrusive ways. Wearables are used to track athletes' performance, emergency states of people with various disorders and overall everyday activities. Using wearables, people's involuntary physiological processes which are known to indicate stress can be tracked and give that feedback to people so that they can act on it. Thus, the challenge is to establish a reliable way to indicate stress levels to the user (students and/or working people) by making use of wearable(s) and stress indicators that can be measured by them. Such indicators are Heart Rate Variability (HRV), Skin Conductance (SC) and Sleep Quality. This leads to the formulation of the main research question: "How can heart rate variability, skin conductance and sleep quality be used in order to determine stress?". The significance of the three indicators, their relation to stress and how they have been/can be measured and use through wearables will be discussed in Chapter 2 through a literature review as well as a State of The Art analysis. Two research sub-questions were defined as well, one to narrow down and one to expand on the topic. Research sub-question 1 is: "Can a relationship be identified between all/some of the three indicators: heart rate variability, skin conductance and sleep quality?". Research sub-question 2 is: "What suggestions can be given to university students in order for them to adjust their schedule in an optimal way to reduce stress levels?". In Chapter 3 an ideation will carried out such that it produces an idea as to how to address the problem. This idea will be further elaborated on and defined further in Chapter 4. The realisation of the idea will be laid out and afterwards evaluated in Chapter 6. Chapter 7 presents the discussion, limitation as well as the suggestions for future work.

Chapter 2 - Background research

In this chapter, the background research related to the previously posed research questions will be presented. Consisting of two parts: Literature review and State of The Art (SToA) analysis, it aims to explain the relationship of HRV, SC and Sleep Quality with stress and the relationship of HRV, SC and Sleep Quality with wearables.

2.1. Literature Review

Wearable technology forms a part of the daily lives of many people. Regardless of their form, shape and functionality, wearables are appearing more and more as the Smart Wearable market continues to expand [11]. With concepts such as the Internet of Things (IoT) which are being researched and implemented on a big scale, it is not surprising that people are (and will continue to be) looking to keep up and make the most out of technologies and their applications. Since wearable devices are such that are to be incorporated into clothing or worn on the body like accessories [12], they can further help with that. As such, there is still a lot of untapped potential in terms of applications, technologies and user needs. One area that has a lot of potential is the one of (physiological) indicators of stress that can be measured daily. Identifying such and presenting a reliable and consistent connection between them can bring new possibilities for people to approach their everyday life.

To tap into the potential of such possibilities, an understanding of the connection between stress and (involuntary) physiological processes is needed. Therefore, this literature review aims to investigate such processes (heart rate variability, skin conductance, sleep quality) and give insight as to what they are and how they relate to stress indication. Consisting of three parts, this literature review, will firstly provide insight into the nature of heart rate variability and how it can be used for stress indication. Afterwards, the same will be done for skin conductance and sleep quality.

2.1.1 Heart rate variability

Heart rate variability is a rather complex matter. To address what it is, what controls it and how it acts, insight into the autonomic nervous system (ANS) is needed. ANS is responsible for regulating involuntary physiological processes, as mentioned by Waxenbaum, Varacallo, and Reddy [13]. One such process is heart rate. Heart rate is defined as the number of heartbeats occurring per minute [14]. The heartbeats do not occur at the same rate, though. Thus, another parameter is present - heart rate variability (HRV). HRV is the measure which indicates the variations in timing between consecutive beats [16]. This measure is connected to the two main branches of the autonomic nervous system - sympathetic and parasympathetic nervous systems (see Figure 1). The first one is responsible for the “fight-or-flight” responses of the body and prepares the body for strenuous physical activity [15]. The latter one is responsible for the "rest and digest" functions of the body and regulates basic bodily function during rather light activities. Depending on the activity that people are carrying out one of those systems prevails. Consequently, different processes are triggered.

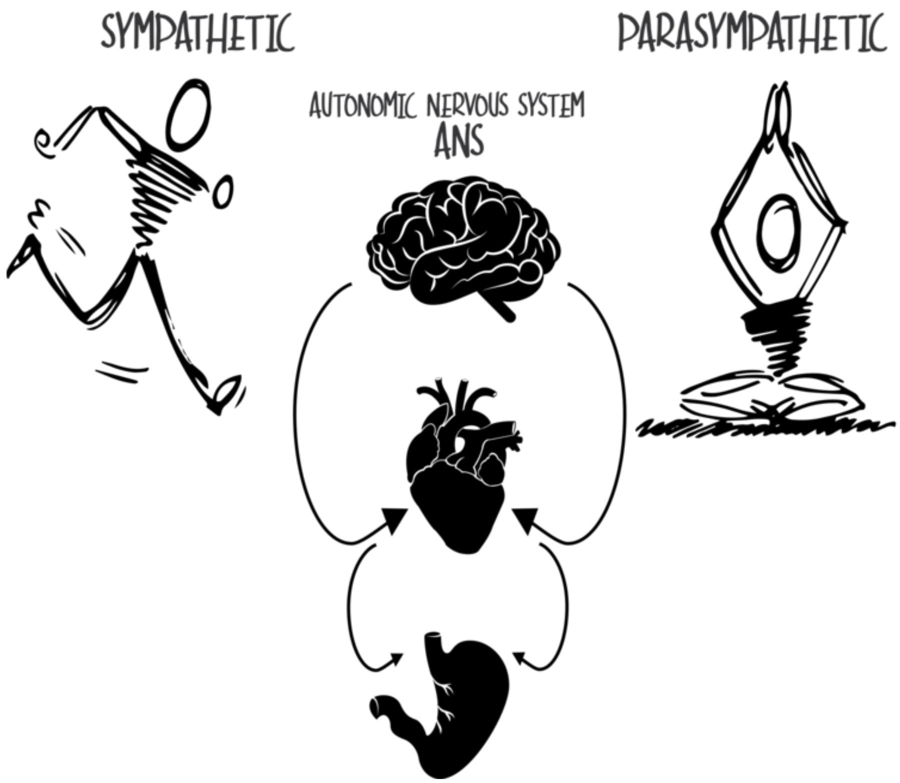

Figure 1. Autonomic nervous system; Sympathetic and Parasympathetic branches [61]

Heart rate variability has been established as one of the indicators of exposure to stressors. Whether stated directly or through mentioning accompanying factors literature is on the same page when it comes to HRV as an indicator of stress. For example, Hansen, Johnsen, and Thayer [21] and Chandola et al. [22] state directly that there is a negative correlation between heart rate variability and stress. On the other hand, there is research which mentions a connection to either the autonomous nervous system as a whole (Malik et al. [24]), or by mentioning concretely one of its branches ([17]-[20], [22], [23]). Regardless of the way they have put it, in literature about heart rate variability and its functions it is indicated that the autonomous nervous system is involved and thus, there is a correlation between HRV and stress.

Heart rate variability is directly connected to the autonomic nervous system and its branches. Taelman et al., Matthews et al., Tharion, Parthasarathy, and Neelakantan [17-19] have all used it as a key measure in their research to determine if its value is tied to the parasympathetic nervous system and sympathetic nervous system and their (im)balance. Matthews et al. [18] report decreased parasympathetic

HRV in students during examinations and Chandola et al.[22] and Tharion, Parthasarathy, and Neelakantan [19] indicate that there is an advantage towards the sympathetic nervous system response. To conclude, HRV is an indicator of reduced parasympathetic activity, which means that when exposed to stressors, people's response that is responsible for calming processes down is underperforming.

2.1.2 Skin conductance

To address the topic of skin conductance, what it is and how it acts, insight is needed on what the skin is. The skin is the largest organ in the human body, there are a lot of processes in which it participates. Also, it is highly innervated. As such, "autonomic innervation of sweat glands is reflected in measurable changes in skin conductance at the surface, termed electrodermal activity (EDA)" [25]. Here, again, a connection is observed with the autonomic nervous system and in particular one of its branches – the sympathetic nervous system. As put by Critchley [25, p. 132]: "EDA reflects activity within the sympathetic axis of the autonomic nervous system". When considering the term "skin conductance" it has to be noted that there are two components of EDA which refer to skin conductance: "Tonic components are slow-changing SC in response to nonspecific stimuli, whereas phasic components are fast variations in SC in response to specific stimuli" [26] (see Figure 2). The first one can be also defined as skin conductance level (SCL), the latter one as skin conductance response (SCR).

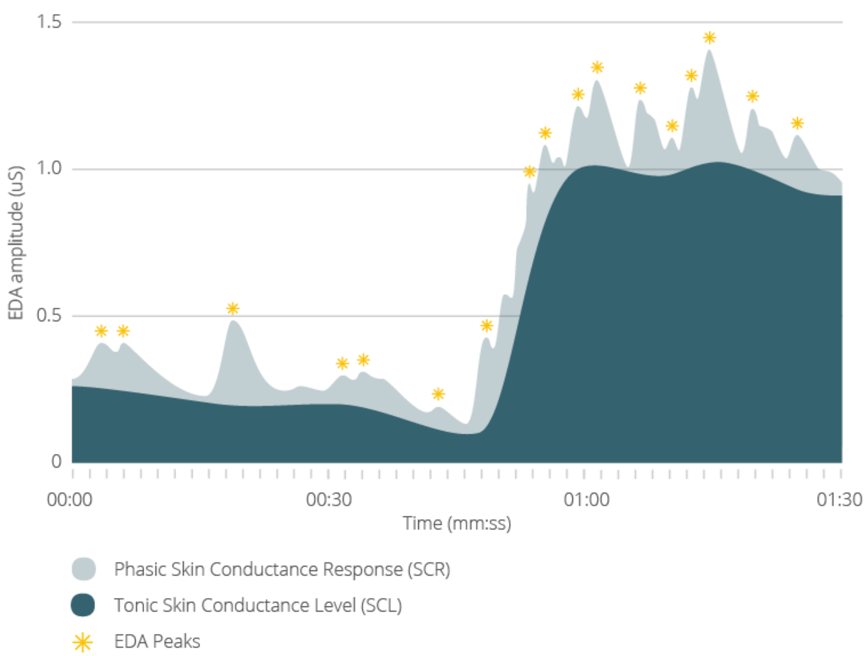

Figure 2. Electrodermal activity. Phasic and Tonic components [60]

Skin conductance is connected to the autonomic nervous system and its branches. As mentioned earlier the autonomic nervous system's activity is the response to stressors. Fechir et al. [27] evaluate their participants to determine changes in SCL and SCRs and conclude that they are due to activation of the sympathetic nervous system. Bari et al. [26] used a different method to induce stress and measure EDA to determine an increased sympathetic activity which "leads to increase in SC and consequently SCRs_ris" [26]. Dawson, Schell, and Filion [28], who provide an especially extensive analysis of EDA, state that "unlike most ANS responses, it [EDA] provides a relatively direct and undiluted representation of sympathetic activity". The first two studies (Bari et al. [26] and Fechir et al. [27]) have taken into account different aspects of SC and methods for inducing stress. Dawson, Schell, and Filion [28] provide an analytical approach. Regardless, they all come to the same conclusion – skin conductance is an exclusive indicator of the activity of the sympathetic nervous system.

Skin conductance is commonly known as a psychophysiological indicator. Psychophysiological stress refers to the physiological response (such as the ones produced by the activity of ANS) in combination with an emotional response [29]. In their study, Bhoja et al. [29] indicate that "The presence of sympathetic activation reported by psychophysiological indicators provides objective evidence of a stressor-induced physiological response." In other words, whenever changes in EDA (and HRV) are present, there has been sympathetic activation which is a result of the body's physiological response to introduced stress.

In their extensive review, Dawson, Schell, and Filion [28] state: "EDA is a sensitive peripheral index of sympathetic nervous system activity that has proven to be a useful psychophysiological tool with wide applicability" which further confirms the findings of Bhoja et al. [29]. Even though, in the literature above, SC is not directly mentioned as an indicator of stress, it can be deducted that it is such. This is due to the fact that EDA (and consequently SC since it is under the umbrella term EDA) can be considered as an indicator of stress, since it is a psychophysiological indicator and represents the way the body reacts to stressors through the autonomic nervous system.

2.1.3 Sleep Quality

Sleep (in its various forms) is an essential part of the existence of every being. As such, its quality is of utmost importance for one's proper function. To understand its nature, a definition is needed. After thorough analysis, Nelson, Davis, and Corbett [31, p. 149] define it as: "an individual's self-satisfaction with all aspects of the sleep experience that can be measured by the following variables: sleep efficiency, sleep latency, WASO (Wakefulness after sleep onset or the "wakefulness, excluding the wakefulness occurring before sleep onset" [79, p. 2]), and sleep architecture measures.". Here, it is important to mention that the sleep quality depends on the subjective opinion of the individual on their experience with regards to measures which can be evaluated objectively.

Sleep Quality can be used as a measure for stress. Various studies explore the connection between sleep quality and stress in different contexts. Querstret and Cropley [30] state “Compromised sleep quality was also a significant predictor of AF and CF.” (AF and CF have been defined as “chronic work-related fatigue (CF) and acute work-related fatigue (AF)”). Even though stress is not explicitly mentioned in that statement, the authors indicate that fatigue is a result of accumulation of stress and improper recovery. Furthermore, it is mentioned that the causality between sleep and fatigue is hard to establish since the two variables can influence each other in a two-way fashion. Herawati and Gayatri [32] study the stress levels in a student environment and find that “Students are with poor sleep quality 4.7 times more likely to have higher stress than students who have a good sleep quality.”. Alotaibi et al [33] also find that there is a significant association between sleep quality and stress when it comes to medical students and their way of living. Regardless of the way that it is put, it can be concluded that there is a connection between sleep quality and stress, but it could be that the two can influence one another in a two-way fashion [30].

2.1.4 Discussion

The human body and its functionality are very complex. As such, a lot of knowledge in the field of physiology is needed to explain processes. In this literature review, the focus was placed not so much on their nature, but rather on how they relate to stress. As a result, there could be details that were missed in this research due to a shallow understanding of the full physiological functions of the human body and the related terminology. As a consequence of the limited amount of time for the research, a limited amount of literature was reviewed. As such, when considering more literature, a different or a more precise result could be achieved. In the work from Herawati and Gayatri [32] unusual and/or odd English language use was noticed as it can be observed in the quote in the previous section. That makes their work quality somewhat questionable, but it is believed that it is peer-reviewed because of where it was published, thus is considered legitimate. For future research on the topic, it is recommended that a more in-depth analysis is carried out, together with more literature. Furthermore, a possible correlation between the investigated indicators (HRV, SC and sleep quality) could be an interesting point for future research.

2.1.5 Conclusion

This section aimed to investigate sleep quality and two variables (heart rate variability and skin conductance) in their capacity of involuntary physiological processes and give insight as to what they are and how they relate to stress indication. When it comes to HRV and SC, it can be deduced that, regardless of the way it is put, the autonomous nervous system is involved. This system is the main indicator of how the body is coping with external and internal factors. The internal balance of the autonomic nervous system, through the sympathetic and parasympathetic systems, is adjusted according to the stimuli (potentially stressors) to which a person is exposed. As a sub-product of that, involuntary physiological processes such as heartbeat (and consequently heart rate variability) and electrodermal activity (which is the umbrella term for the two main components of SC) are being altered. Research shows that HRV is an indication of reduced parasympathetic activity, meaning that under stress the body is underperforming in terms of achieving a state of calmness. When it comes to skin conductance, from literature, it appears that it is an exclusive indicator of the activity of the sympathetic nervous system, meaning that when put under stress, the body tends to tilt the balance towards a state of/ready for turbulence. As the two measures both indicate the activity and balance of the autonomous nervous system and are psychophysiological measures of stress there might be a connection/correlation between them. When it comes to sleep quality, it was established that there is a connection between this measure and stress, but the two can influence one another in a two-way fashion.

2.2 State of The Art (SToA)

The State of The Art analysis is directed at the three physiological indicators of stress and how they relate to existing or conceptual wearables. The analysis is split into four parts: Smart Rings, Wrist wearables, Professional/Medical wearables and Heart rate monitors.

2.2.1 Smart rings

2.2.1.1 Oura ring

One of the most popular options when it comes to smart wearable rings is the Oura Ring (3rd generation, Figure 3) [34]. Its functionality comes down to three main components: “Sleep”, “Activity” and “Readiness” which are all addressed in the form of scores and presented to the user. The sleep score is addressed as “How well did you sleep last night?” [35]. It is based on 7 elements: total sleep, efficiency, restfulness, REM sleep, deep sleep, latency and timing. The Activity component keeps track of how active the user is (in terms of light activities such as moving a little bit from time to time, as well as training/workouts) and if they have enough recovery time. The last component – Readiness, is based on the previous two and “body stress”. This component is explained as follows: “Readiness is a holistic picture of your health — taking into account your recent activity, sleep patterns, and direct body signals (like resting heart rate, heart rate variability, and body temperature) that can signify if your body is under strain.” [36]. Here it is important to note that there is a combination of components, two of which are “sleep patterns” and HRV, that are used to indicate if the user is under stress. To conclude, the Oura ring is a smart wearable product which uses two (HRV and sleep quality) of the three components (HRV, SC and Sleep quality) central in this study and based on them presents the user with a type of stress level.

Figure 3. a) Oura Ring Gen3; Horizon; Gold [54]

2.2.1.2 Circular ring

The Circular ring [37] (Figure 4) is another rather popular option for a smart ring. Even though it is still not mass released it is available for purchase. It also provides various ways to track everyday activities. Here, it is important to mention that there are sleep and activity analyses which present the user with scores (similar to the Oura ring). It also includes calculation of HRV. The official information about the Circular ring is focused on marketing the product due to the stage of the company's development. In a brief explanation, Sawh [38] states that the Circular ring "supposedly helps you monitor wellness". It is unclear what wellness concerns but stress levels are a part of overall wellness, so it could be related to stress. From the mentioned above it can be concluded that the Circular ring is a wearable, similar to the Oura ring, which provides measurements of HRV and sleep and relates them to wellness.

Figure 4 Circular ring; Silver [55]

2.2.1.3 Happy ring

The Happy ring [39, 40] (Figure 5) is another example of a smart ring. It is/will be supposedly “The first wearable for your mind” [40]. Official information on the product and its functionality is hard to find but both Boxall [41] and Stables [42] mention it will include a custom EDA sensor as well as heart rate and sleep tracking and that it will track stress. Even though the integrity of this information could be questionable since it is not provided on the official website or media of the product, the idea behind the ring sound very promising since on top of heart rate (HR) and HRV, it will include/includes EDA measurements which are known to be an indicator of stress (as mentioned in Section 2.1.2).

Figure 5 Happy ring [40]

2.2.2 Wrist wearables

2.2.2.1 Apple Watch

In terms of smartwatches in the last few years, Apple has had the biggest market share in the wearable market [43]. Their Apple Watch [44] (multiple ones in Figure 6) and its various generations are the most popular option when it comes to wearables. The latest watch operating system (watch OS 9) and watch generations (Series 8, Ultra and Special Edition) will be considered. There are not any reports of using measurements for the identification of stress or mental wellness (even though there is a Mindfulness application from Apple). Apple's smartwatches measure HR and consequently calculate HRV but overall they are used for tracking physical activity. There is also a possibility to take an electrocardiogram (ECG). Furthermore, Apple's watches "can estimate the time you spent in each sleep stage—REM, Core, and Deep—as well as when you might have woken up" and track the nightly wrist temperature [45].

Figure 6 Apple watches [56]

2.2.2.2 Garmin

Another big name on the market of wearables is Garmin (Figure 7). They have a few lines of wearables each marketed for different purposes and sports. Most (if not all) of them measure heart rate and calculate HRV. Garmin also has an "HRV Stress Test" [45], which when prompted by the user (and with the compatible devices) can provide the user with a stress level based on their HRV. Garmin also provides all-day stress tracking based on HR and HRV which provides the user with a 0-100 stress score. Even though the type of stress that is tracked is not indicated it is said that the stress tracking stops during physical activity to account for the fact that the user can be under stress because of the physical strain [78]. Additionally, as with some of the previously mentioned wearables, some of Garmin's such, can provide the user with a sleep score and indicate the quality of their sleep. It takes into consideration the following parameters: Sleep Duration, Average stress score during sleep, Total deep sleep, Total light sleep, Total REM sleep, Awake time and Restlessness.

Figure 7. Garmin products [63]

2.2.2.3 Fitbit and Google

Another company worth mentioning is Fitbit. The company is related to Google, so the Fitbit Sense 2 (and the rest of the Fitbit products) and the Google Pixel Watch (see Figure 8a) are being sold in one place. Both of these flagship devices of the two companies have the capabilities to calculate HRV from HR. Similar to previous wearables mentioned they also offer sleep tracking and sleep stages as well as a sleep score. Fitbit's Sense 2 (Figure 8b), though, offers some additional functionality – "EDA sensors, plus heart rate, heart rate variability and skin temperature tracking, help your Fitbit track physical indications of stress" [46]. A "Stress Management Score" can also be seen by the user, this one is based on HRV, activity and sleep. On top of that, users can log their moods throughout the day and indicate that they feel (for example) stressed.

Figure 8 a) Google Pixel Watch – Black (left) [62] b) Fitbit Sense 2 Shadow Grey / Graphite Aluminum [57] (right)

2.2.2.4 Whoop 4.0

When it comes to wrist wearables there is one somewhat unconventional product that has to be mentioned – Whoop 4.0 [47] (Figure 9). It is unconventional because, contrary to its competitors, it does not include a screen, it is intended to be charged on the user's wrist and there is an additional option to wear it on the bicep. In terms of functionality, it can measure the heart rate (and calculate HRV), it provides sleep tracking and, as of recently, can measure stress levels based on resting heart rate (RHR) and HRV.

Figure 9 Whoop 4.0 [58]

2.2.3 Professional/Medical wearables

Some wearables are designed for professional/medical purposes. Examples of such wearables are the Embrace Plus from Empatica [48] (Figure 10), four wearables (one of them available only for pre-order) from ActiGraph [49] and two wearables from Activinsights [50]. These wearables aim to provide users, patients, researchers or medical staff with information of interest in the long term. The wearable from Empatica seems to provide the largest pallet of data by including EDA, in contrast with the other wearables which provide information on HR, body temperature, sleep and overall activity.

Figure 10 Embrace plus by Empatica [59]

2.2.4 Heart rate monitors

Another popular type of wearable is the heart rate monitor. For the most part, they are designed for people who lead an active lifestyle and want insights into their performance based on their heart rate while carrying out sports activities. Such wearables are usually in the form of some type of elastic band that can be strapped to the chest or somewhere on the arm. Some examples of such are the wearables from Polar [51] and Scosche [52]. They do not offer much else than heart rate analytics, but it seems that they have higher accuracy than wrist-worn devices which have the same aim.

2.2.5 Discussion

In this part (Section 2.2) a SToA analysis was carried out to determine how the three physiological indicators (HRV, SC and Sleep Quality) of stress relate to existing or conceptual wearables. As such, the technical information about the wearables presented was not considered/researched in depth. Consequently, it is difficult to determine if the wearables perform well when it comes to the tasks that were discussed. Additionally, due to the amount of wearables some of the companies offer, it is difficult to consider all of them and their separate details. Another aspect which is important to mention is that the companies might intentionally leave out information on the exact functionality of their products to protect their business. This raises some doubts as to what type of stress is measured with the wearables that provide this functionality. The term "stress" is often interpreted in various ways, and wearable technology companies may not specify what type of stress their devices measure. It is important to note that when the term "stress" is used by them, it should not be automatically assumed to refer solely to mental stress, as it could encompass other types of stress, such as physical strain (addressed by Garmin, as mentioned in Section 2.2.2.2). This is why in the summary of this section in Table 1, in the "Mental stress" column the word "Supposedly" is used to indicate that a stress measure is implemented but it could be more or different than just mental stress. As such it is important to mention that this research aims to address not just any stress but it will be focused on mental such. Furthermore, it is important to note that a limited amount of products was considered due to time constraints. Given those limitations, it could be that a more thorough and/or extensive State of The Art analysis could lead to different conclusions. Thus, for future research, it is recommended that more in-depth analysis is carried out.

2.2.6 Conclusion

In general, all the wearables presented in this section use very similar ways to present users with the information. Phone applications offer a lot of graphs, metrics and scores; some of them provide the user with suggestions as to how they should act (direct advice), others provide guided sessions and some leave it up completely to the user to act on the score, percentage or metric they are presented with. The most common ones are: raw numbers, bar graphs, line graphs, percentages and scores calculated based on an algorithm or a formula from the manufacturer/developer. Identifying the "best" methods is rather impossible since these wearables are targeting a range of users which is as wide as possible and thus there are aspects which might be appealing to one user group but not to another.

All of the wearables in this State of The Art analysis were considered in such a way that they include at least one of the three physiological indicators (HRV, SC and sleep quality). It has become evident that the standard, for everyday wearables in the industry, is a wrist worn wearable, most often – a smart watch. A summarized version of the analysis can be observed in Table 1.

Table 1 Summary of the SToA findings

Type of wearable	Wearable/ Company	HRV	EDA /SC	Sleep quality	Mental Stress	Stress through:	Stage of development
Rings	Oura Ring (Gen 3)	Yes	No	Yes	Supposedly	HRV and Sleep	Mass market
	Circular ring	Yes	No	Yes	Supposedly	HRV and Sleep	in Beta but available for purchase
	Happy Ring	Yes	Yes	Yes	Yes	HRV, SC and Sleep	Unknown
Wrist worn wearables	Apple Watch	Yes	No	Just sleep	No	N/A	Mass market
	Garmin	Yes	No	Some	Supposedly	HRV	Mass market
	Fitbit (Sense 2)	Yes	Yes	Yes	Supposedly	HRV, SC	Mass market
	Whoop 4.0	Yes	No	Yes	Supposedly	HRV	Mass market
Professional/ medical wearables	Empatica (Embrace Plus)	Yes	Yes	Yes	No	N/A	Limited access
	ActiGraph	Yes	No	No	No	N/A	Limited access
	Activinsights	Yes	No	No	No	N/A	Limited access
Heart rate monitors	Heart rate monitors	Yes	No	No	No	N/A	Product

It can be concluded that HRV is considered an essential variable and companies which offer wearables implement it regularly. The second most implemented aspect is various measures of sleep. For the most part, the sleep elements, taken into account for the wearables presented above, can be related to the aspects mentioned in Section 2.1.3 given by Nelson, Davis and Corbett [31] to explain sleep quality. A segment that is somewhat lacking is the one of SC. There are not many wearables which provide EDA measurements or analysis but that seems to be changing, given that the Happy ring (see Section 2.2.1.3) is said to be implementing such a feature and that it already has been implemented in other commercial and professional wearables. As for stress, there are wearables which have implemented/will implement it as a parameter but so far there has not been a solution which provides a measure of stress based on all of the three parameters – HRV, SC and Sleep Quality. Here, Happy Ring (see Section 2.2.1.3) is the closest that comes to such a solution but given the amount and quality of information, it can still be considered to be a highly conceptual product. The Fitbit Sense 2 also provides the possibility to measure all three of the physiological elements and measures stress but not based on all of them. Fitbit also offers Application programming interfaces (APIs) with which apps and clock faces can be built. The design of the wearables was not analysed in depth but there are a few obvious aspects. One was that the smart rings considered in Section 2.2.1 appeared to be rather bulky (in general but also when compared to normal rings). On the other hand, they appear to be a better option than other types of wearables when it comes to wearing them during sleep. The two wearables which have the capability of measuring the three, core for this study, elements are the Fitbit Sense 2 and the Embrace Plus from Empatica.

Chapter 3 – Ideation

Having carried out the Background research (see Chapter 2), the ideation process will be discussed in this chapter. To do that, an overview of the findings in Chapter 2 is to be provided. So far, it has been established that HRV is mainly a representative factor of the activity of the parasympathetic nervous systems, while SC is such a factor for the activity of the sympathetic nervous system. Worse sleep quality is an indicator of stress (but stress can also be an indicator of worse sleep quality, so the matter should be approached with caution). The State of The Art analysis showed that there are wearables which can measure one or more of the three indicators (but there are not many which measure EDA) there are also wearables which can measure stress based on one or more of the three indicators (but not any which measure it based on all three).

3.1 Step 1 – Mind map

In this chapter, as well as the next three (chapters 4, 5 and 6), the Design process for Creative Technology presented by Mader and Eggink [53] will be used as a stepping stone. To begin the ideation process, a lateral thinking technique can be used. Since at this stage the ideation is done by one person an appropriate technique is to create a mind map (Figure 11). “Mural” was used as the software for creating the mind map.

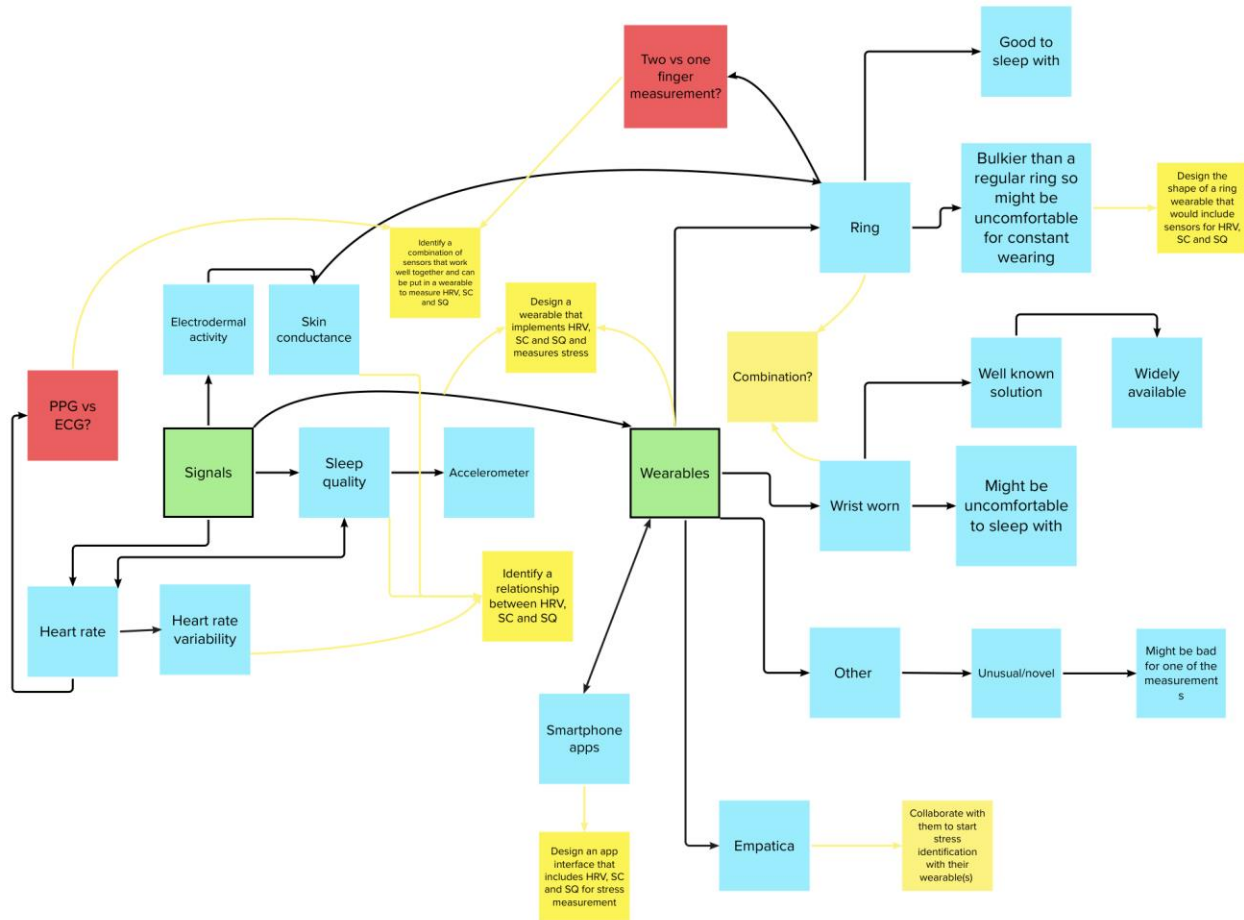

Figure 11 Mind map created after the Background Research;

This brainstorming session was time restricted to two periods of 30 minutes. This was done so that the brainstorming process/session would not be prolonged unnecessarily and was split in two to allow for a small break and a reset of cognitive processes. On the mind map the core elements are “Wearables” and “Signals” (which represent HRV, SC and sleep quality). Blue elements are normal connections which have emerged. Yellow elements indicate ideas; red elements indicate (rhetorical) questions. For convenience the seven ideas which immerged from this technique are listed here (some of them rephrased to represent the true meaning) in no particular order:

[Idea 1] Identify a combination of sensors that work well together and can be put in a wearable to measure HRV, SC and SQ

[Idea 2] Design a wearable that implements HRV, SC and SQ and measures stress

[Idea 3] Identify a relationship between HRV, SC and SQ

[Idea 4] Design an app interface that includes HRV, SC and SQ for stress measurement

[Idea 5] Design an optimally comfortable shape of a ring wearable that would include sensors for HRV, SC and SQ

[Idea 6] Design a combination between a ring and a smart watch/bracelet

[Idea 7] Collaborate with Empatica to implement identification of stress with their wearable(s)

One more idea emerged as a result of the State of The Art analysis. As mentioned in Section 2.2.5, there are two wearables which are suitable for the purposes of this study: Embrace Plus by Empatica and Fitbit Sense 2. An idea related to the first one already emerged during the mind map brainstorming session. A similar approach can be used with the Fitbit Sense 2. Thus, Idea 8 would be to "Use Fitbit Sense 2 and the Web APIs to implement identification of stress using HRV, SC and sleep measurements"

3.2 Step 2 – Stakeholders

So far stakeholders have hardly been considered but it is important to identify such as well as their needs and requirements. In Section 2.1 literature containing different methods of testing and including different age groups was discussed. Some of the research was based on students and some was based on working people. Even though stress is experienced by everyone and everywhere, a priority has to be put on a certain group.

3.2.1 Main stakeholders (target group)

In this study, students are to be the target group or the main stakeholder group. This is done for a number of reasons. Students' way of living appears to be less monotonous compared to people who are working (especially a 9-to-17 job) because they are more prone to try new activities, for example, and their schedules are more volatile. This introduces exposure to more and different type of stressors on a daily basis. This allows for researching a wider spectrum when it comes to stress. Understanding this spectrum and accounting for it can be used as a foundation to target different user groups in the future. Additionally, due to the place where the study takes place and the restrictions in time, recruiting participants for potential testing is easier.

3.2.2 Other stakeholders

When it comes to other stakeholder groups it is important to consider that they can be the ones being impacted or the ones that make an impact. An example of a group that can be impacted is the one of owners of wearables. In general, their preferences, behaviour and wishes might shift or change if certain novel application or interaction is achieved with existing or new wearables. The third stakeholder group is one of people concerned with helping others deal with stress. This can include psychologists, psychotherapists, counsellors, mentors, life coaches and various arts and sports instructors. Their way of working with people could potentially be altered but also they might become concerned with the safety of their clients/patients. Companies which sell wearables are another type of stakeholder. Their business and approach to designing new devices might be impacted. The last group of stakeholders which can be impacted is the one of acquaintances, friends and family of the users since their relationships can be influenced. Governments, (non) governmental organizations, unions and other institutions are examples of stakeholders which can make an impact. As such they can allow, restrict and forbid research and/or development of certain products, applications, frameworks, projects, etc.

3.3 Step 3 – Preliminary requirements

Having identified a few groups of stakeholders, it is important to consider preliminary requirements. Since there is no final concept at this stage, non-functional requirements can be set to concretize and possibly get one step closer to reaching a final concept. They will be posed such that they would rather guide (in terms of design) the ideas from Section 3.1. To do that, another look at the State of The Art analysis is needed. Some of the existing wearables have screens, which often display a simplified/summarized version of the information to the user. Since presenting the user with the full range of information is challenging on the small screen of the wearable, companies often either develop their smartphone applications or allow the wearable to be connected to third-party smartphone applications. For the wearables which do not have screens, smartphone apps are even more essential. Consequently, one requirement is for the information to be presented conveniently according to the device it is presented on. A requirement that can be identified in terms of smartphone applications is that such an application should have an intuitive design for the user, simple enough to interact with without a need for training. Also, information in the application should not be too much (not at once at least) or crammed so that users will not be overwhelmed by it. Those three requirements (also listed below as Preliminary Requirement (PR) 1, 2 and 3 for convenience) are especially connected to research sub-question 2 posed in Chapter 1 since its essence is related to the conveyance of the information.

Information is well suited for the form-factor of the device it is presented on [PR1]

A potential (smartphone) application should have an intuitive design, simple enough to be used without a need for training [PR 2]

The amount of information should not be too big as to no to overwhelm the user [PR 3]

3.4 Step 4 – Elimination of ideas

After having generated some ideas, identified stakeholders and preliminary requirements, it is time to go back and over (as per the Design Process for Creative Technology [53]) to evaluate the ideas and to explain the preferred concept and the argumentation for it. Let us start with Ideas 2 and 6 from Section 3.1. These two ideas are considered to be the most ambitious ones since they involve elements from all the other ideas. Due to time restrictions, limited resources and the complexity of the tasks involved in the realization those ideas are not deemed feasible. Ideas 1 and 5 have a common element - identifying a combination of sensors for HRV, SC and sleep quality measurements for a wearable. The difference is that in the case of the latter idea the sensors will be chosen in such a way to fit into a predesigned shape of a ring. The results of the realization of these two ideas can easily be disregarded rather quickly due to the rapid development of new technologies and sensors for such devices. Idea 3 would address research sub-question 1 perfectly and it will be a good foundation for further research but to realize such an investigation properly, a lot of preliminary knowledge about the physiological functions of the human body is required (which is a limitation, not only for the literature review as mentioned in Section 2.1.5, but also for the whole study). Ideas 4, 7 and 8 are left. They have good potential although there are some points which have to be addressed. One point is that there is some overlapping between Idea 4 and the other two ideas. If either one of Idea 7 or 8 is to be realized, then an application interface is unavoidable. Realizing Idea 4 would not bring too much novelty and will not be very useful for further research/implementation since it will be a digital design product including mock-up measurements. Companies which develop and sell wearables have more resources and thus, bigger teams of professional designers, possibly with years of experience, on which they would rely to design such a digital product with implementation of the measurements suited to and produced in a specific way by the company. On the other hand, choosing a framework to work with and build on top of, creates a possibility to create a complete solution which accounts for all the Research Questions (see Chapter 1). For that, Ideas 7 and 8 seem to be the most suitable.

3.5 Step 5 – Preferred concept

From Ideas 7 and 8, Idea 8 is the preferred one. When comparing them not much difference can be observed regarding the concept, but there is one element which is key for considering one to be more suitable than the other. As mentioned in Section 2.2.5, the two wearables which can measure the three core elements for this study are the ones from Empatica (Embrace Plus) and Fitbit Sense 2. The philosophy of those companies differs quite a lot. The main aim of the first one is to help (medical) professionals, researchers and patients with solutions which are scientifically known to work. The latter would aim to create solutions for the mass market. The key factor is accessibility. Even though Empatica would most probably support a research when it comes to physiological elements and stress, such a solution will be less accessible for the main stakeholder (a university student) daily. Ultimately, Idea 8 is the preferred concept.

Chapter 4 – Specification

This chapter aims to provide a more elaborate description of the idea as well as its functional requirements. The preferred concept, mentioned in Section 3.5 as Idea 8, refers to using a Fitbit Sense 2 and Fitbit's Web APIs to implement identification of stress using HRV, SC and sleep measurements. Even though it was not explicitly mentioned in the previous chapter this idea was chosen such to address a crucial functional requirement for a wearable with the described functionality – the wearable should be capable of measuring the user's heart rate variability, skin conductance and sleep quality. Given that the current study does not have a budget it was important that the costs are kept low and wearables could be borrowed instead of rented/bought. It was discovered that the Interaction Lab in the University of Twente owns two Fitbit Sense smart watches which were available for reservation, but they are first generation. Given that both generations are capable of measuring the user's heart rate variability, skin conductance and sleep metrics (as part of assessing sleep quality) and with an intention to keep costs low it was decided that the target wearable for the study will be a Fitbit Sense (1st generation). After a more thorough exploration of what Fitbit's Web APIs offer in terms of functionality it was determined that even though the wearable has the capability to measure EDA, the measurements cannot be accessed through the Web APIs. Given this finding and the fact that after the State of The Art analysis there was no other wearable on the mass market which could measure all of HRV, SC and sleep metrics it is decided that skin conductance is to be disregarded from the scope of the current research. Thus, the main research question and research sub-question 1 (see Chapter 1) respectively change as such: "How can heart rate variability and sleep quality be used in order to determine mental stress?"; "Can a relationship be identified between the two indicators - heart rate variability and sleep quality?".

4.1 Procedure

Since stress is the measure of interest, it is the dependent variable, and given that HRV and sleep quality will be used to determine it, they are the independent variables. As mentioned in Section 2.1.3 sleep and stress can influence one another in a two-way fashion. The relationship between them is of interest to the study, so to explore it, data is needed. This relationship could be found by analysing trends visually or statistically, one by one or all at once.

Data will be gathered from representative of the target group (described in Section 3.2.1) users. Initially, the researcher's data will be used for building an algorithm/script that gathers the required data and processes it (as much as possible). A number of participants will be recruited. Participants will be given a wearable and asked to wear it consistently for 3-4 days which will include workdays and weekend days. This will provide a substantial amount of data and account for a range of different situations. As such, participants will be also asked to provide a rough schedule for the days when they participate in the data collection. In the present user study, the participant sample will be restricted to male individuals. This decision is based on variability in indicators (e.g. HRV) between male and female subjects as shown by Umetani et al. [64]. To maintain consistency in the study population, female participants will not be included in this investigation. The aim is to recruit 3-4 participants. Their HRV and sleep metrics are the ones which will be measured with the wearable. Participants will be given forms and asked to fill them out daily. They will have to evaluate their sleep experience and evaluate their stress levels on an Ottawa stress scale (see Figure 12) [66] a number of times per day (every two hours). The Ottawa stress scale was chosen its Likert-type scale is further split into 5 sections which prompts the participant for further contemplation which can elicit better/more precise results. Furthermore, this scale implements pictorials which help the user relate to a visual representation of their feeling/assessment for mental stress.

After obtaining the data it will be processed and analysed. Fitbit devices calculate HRV only during the longest sleep over a 24-hour period [67] and the parameter which could be obtained through the Fitbit Web API is RMSSD – "root mean square of successive differences between normal heartbeats" [65]. An "HRV Intraday" request for a given date/interval returns a json-type response containing the following elements: date, the given time of the measurement, RMSSD value, coverage, high-frequency band power and low frequency band power [71]. Furthermore, these values are given for every 5 minutes. Obtaining such a value for the day hours is needed.

When it comes to processing sleep metrics, the request for "Sleep Log" request returns a json (JavaScript Object Notation, a text format that is completely language independent [80])-type response containing 28 elements, but the focus falls on: date, duration, efficiency, a Boolean variable determining if the sleep was a nap or a "main" sleep, time and "level" or stage of sleep (deep, light, rem or wake). The self-reported measure will be compared with the Sleep efficiency scores which Fitbit provides. Sleep stages, their duration and distribution, will also be used to compare with HRV and self-reported mental stress levels.

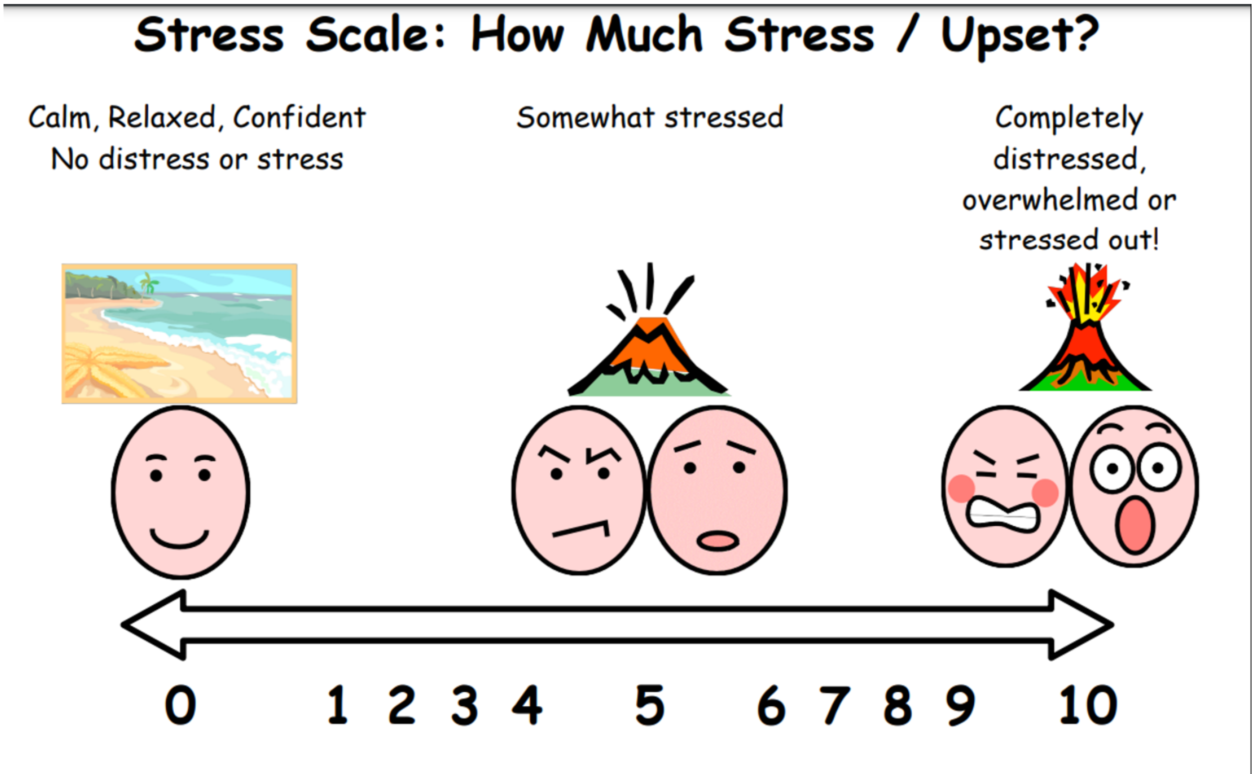

Figure 12. Ottawa stress scale [66]

After the exploration of the relationship between the dependent and independent variables, an application interface will be built to represent it. To identify what aspects will be most suitable for the needs of the users, interviews will be carried out with the testers. The main aim of this will be to gain insight as to what users would like to see/be presented with throughout their day on the screen of the wearable/the phone screen, but also to understand how users felt during the study. A pilot interview will be done to determine the relevance of the questions and their clarity. The interview questions will be discussed with other researchers working in the field of wearables.

Given that this whole procedure involves human participants, an ethical request was made with the Ethics Committee Computer & Information Science of the University of Twente. The request number is 230284. The documents related to that request (informed consent form and information brochure) can be found in Appendix C.

4.2 MoSCoW analysis

Given that the final product of this study is planned to be an application interface, it is reasonable to use the MoSCoW method [59] to expand on the preliminary requirements, steer them to better fit the preferred concept from Section 3.5 and prioritize them (this is done by the researcher). These requirements are made such that they address the prototype (interface) which is to be made as a result of the analysis of the data. The “Will not have” section addresses mainly the fact that the prototype will not have commercial implications. The MoSCoW method consists of 4 categories as follows:

4.2.1 Must Have

The interface must be integratable with an application for a Fitbit Sense smartwatch to collect HRV and sleep data.

The interface must be able to implement HRV measurements and analyse them

The interface must be able to implement sleep measurements and analyse them

The interface must display stress in a user-friendly manner

4.2.2 Should Have

There should be in-app reminders in terms of stress

The interface should take into account the way the application and the smart watch would be synchronized

Sleep quality analysis should be detailed regarding its stages and duration

There should be trend analysis so users can track information over time

4.2.3 Could have

There could be notifications and reminders to encourage users to use stress reduction techniques

There could be implementation of mental stress levels based on HRV and sleep quality

There could be alerts/notifications for significant changes in mental stress levels or sleep quality

4.2.4 Will not have

There will not be suggestions for in-app purchases or subscription-based features.

There will not be integration with non-Fitbit devices.

There will not be medical diagnosis or treatment recommendations.

Chapter 5 – Realisation

In this chapter the realisation of the current study will be presented. The initial expectations of how workable the data was going to be were exceeded and the overall procedure and plan for the study changed. As such, the realization consisted of two parts: Calculation of RMSSD approximation through heart rate and Data collection from representatives of the target group.

5.1 Calculation of RMSSD approximation through heart rate

As mentioned in Chapter 4, Fitbit devices calculate RMSSD only during the longest sleep over a 24-hour period and obtaining such a value for the day hours is needed. This can be done by using the heart rate measurements through the Fitbit Web API to get an approximation of the RMSSD values. Heart rate values are said to be possible to obtain at intervals every second, minute, 5 minutes and 15 minutes [72]. The "Heart Rate Intraday" request returns a json-type response containing quite a few elements for a given date/interval but the most relevant ones are date, time and heart rate value. Prakash and Madanmohan [68, p.57] mention a standard method for calculating heart rate from ECG as: "HR = 60/RR interval in seconds". Even though the Fitbit Sense watch which is to be given to the participants has a PPG sensor which provides a different type of measurement, there is a relationship between ECG and PPG signals as Wu et al. [69] have shown. As such, the formula above can be turned around and used to acquire an estimation of the RR intervals in seconds (duration) for a given heart rate as follows: RR interval in seconds = 60/HR. After obtaining that, every nth-1 RR interval duration is subtracted from nth RR interval duration. This produces approximated RR intervals. Taking the root-mean-square of these intervals over a period of 5 minutes produces the approximation of RMSSD which is on approximately the same intervals as the RMSSD values obtained through the Fitbit Web API.

The Python scripts for acquiring the raw data (according to the description in Section 4.1) and calculating RMSSD from heart rate, as well as putting the data into workable structures can be found in Appendices A and B. A number of libraries were used: *requests* (to make the request to the API), *csv* (to be able to put the processed data into a csv file), *datetime* (to be able to use the timestamps and make computations with them) and *math* (to be able to make square root computations). The raw data is a dictionary containing other nested dictionaries and lists. This format is not very intuitive to work with so the necessary values are extracted and put into lists or float variables such that they become easier to be iterated over and used for calculations (of RMSSD for example or when calculating the consecutiveness of time intervals).

5.2 Data collection from representatives of the target group

According to what was laid out in Chapter 4, the wearable used in this study is a Fitbit Sense. Two wearables were acquired through the reservation system of the Interaction Lab at the University of Twente. Three (apart from the researcher) participants were recruited for the study according to the requirements presented in Section 3.2.1.

To use a Fitbit wearable, the user has to set up an account. Such that the anonymity of the participants was kept intact an email account and a Fitbit account was set up in advance for each of them. Those accounts were set without the use of any information through which the participants could be identified. They were to be given the credentials for said accounts after they had given their informed consents. In order for the data to be extracted through the Web API by Fitbit, one needs to log in with their Fitbit account into the developer system and register an application. After that, they go through the OAuth 2.0 authorization process to acquire an access token which can be used to access data through json requests. That step was carried out separately for the three participants through an Implicit Grant Flow Authorization by the researcher with the initially set up accounts. The access token has been intentionally omitted from the scripts in Appendices A and B for the sake of confidentiality.

Chapter 6 – Evaluation

In this chapter, the Evaluation of the data will be presented. As mentioned in the previous chapter, the overall procedure and plan for the study changed and the Evaluation phase turned into an explorative assessment of the data in order to discover its potential. Due to the complexity of the data and how it was structured, there was no easy way to make it so it fits every possible purpose. As such, it was decided that the data will be processed participant by participant, day by day to create the proper analyses. Additionally, due to the small amount of participants and sample sizes for some of the variables statistical and/or numerical analyses would not have been appropriate. Therefore, a lot of the data was analysed on the basis of Visual inspection which has been shown by Bobrovitz and Ottenbacher [76] to be as reliable, in many cases, as statistical data.

6.1 Data collection

As mentioned in Section 5.2 three people took part in the data collection. They were using the wearables during different periods: participant 1 (P1) used the wearable from 01.06.2023 to 05.06.2023 (4 full days and the night of the 05th of June), participant 2 (P2) used the wearable from 03.06.2023 to 05.06.2023 (3 full days) and participant 3 (P3) used the wearable from 09.06.2023 to 13.06.2023 (4 full days and the night of the 13th of June). Their anonymity will be preserved throughout this report by using the P1, P2 and P3 tags (the titles of figures/dashboards will include an indication of which participant they refer to by making use of these tags). P2 used the wearable for a shorter period of time after reporting that they were not feeling well and would prefer to end their participation early. Each of them was briefed on the procedure, given time to read the Information brochure and signed an Informed consent form.

To remind participants to log their sleep experience and their mental stress levels they were to be sent messages through one of the common platforms for messaging (Whatsapp). Messages were automated to be sent on a fixed schedule from 7:30 every two hours until 23:30. Participants were being sent three messages at 7:30: 1. “Please remember to log what was your overall sleep experience on the scale of 0-10”, 2. A photo of the Ottawa stress scale (Figure 12), 3. “Please log your mental stress levels over the past 2 hours on the Ottawa mood scale (from 0-10)”. Those messages did not have the aim to prompt answers from the participants at the exact time of their sending but rather to serve as a general reminder for them to log the corresponding measures. Shortly after Participant 1 logged their first sleep satisfaction they decided to change their answer for a higher rating. That was allowed because it was concluded to be a result of the people not having a good judgement right after they wake up. As such, the first message for the day was changed to be “Please remember to log what was your overall sleep experience on the scale of 0-10, half an hour after you have woken up” for the rest of the participants and days. The participants were also given the opportunity to choose their preferred method of logging. This was done to ensure that the participants will have the opportunity to log in a way that suits their needs best. The options proposed to them were: a) fill out a daily form printed on paper, b) fill out that same form digitally, c) log digitally through a medium preferred by them and d) reply directly to the reminders in the messaging platform. P1 chose option c), P2 chose option a) and P3 chose option d). After being gathered the self-reported data was manually entered in an MS Excel spreadsheet. The daily form template can be seen in Appendix D.

6.2 Self-reported mental stress analysis

After acquiring the self-reported mental stress levels of each participant and entering them in a spreadsheet the data was visualized with Tableau. Three separate Worksheets were created (for the data of each participant) and later they were combined into a dashboard (Figure 13). It is evident that participants logged data different amount of times. For P1 they are fixed but for the other two participants they vary. First possible reason for that is the fact that people might wake up and go to sleep at different times which simply results in more/less time for logging. Second, the nature of the notification and logging system(s). As mentioned in the previous section, reminders did not have the aim of demanding an immediate response bur they were a rather general guideline for logging which results in more freedom for the participants but also more responsibility on their part.

The bar chart inn Figure 13 helps identify somewhat of a pattern. In 8 out of 11 cases, participants would report a (gradual) increase followed by a dip in mental stress levels somewhere between the late morning and early evening. In the cases of participants 1 and 3 this pattern is more visible. The difference in the timing from participant to participant is due to their different lifestyles and day-to-day activities. For example, in personal conversations, Participant 1 has reported that for the most part, they prefer to complete their tasks for the day at around 18 o'clock, while it is known that Participant 3 prefers to work in the evening hours. Additionally, participants might be employing techniques and completing activities which are known to generally reduce stress (such as sports, meditation or hobbies). When observing the data of Participant 1 for example, this dip can be recognized in the logs from around 15:30 to 21:30. This can be narrowed down even further if a comparison is made between a workday and a day from the weekend. On workdays it can be observed that they happened earlier than on the weekend which could indicate that participants would be done completing mentally stressful tasks or would find ways to reduce their mental stress levels earlier. In the case of participant 3 this relationship is opposed, but also it can be observed that Participant 3's tendency is for increasing rather than decreasing stress levels throughout their days. In Participant 2's data, it is harder to analyse these aspects (likely because of the early end of their participation). To further analyse these relationships and patterns other analyses (visual and numerical) can be made together with the other two metrics collected (RMSSD and sleep metrics). The findings in this section point towards the suggestion that when it comes to mental stress it is highly important to consider people's schedules, and personal preferences regarding when they start their days, when they end them and how they spread out and utilize their schedules. Even though participants have the same main occupation (being university students) and are of the same gender and same age group, their mental stress levels differ drastically in terms of time, levels and even patterns. This indicates that mental stress should be considered a highly personal measure which implements multiple dimensions.

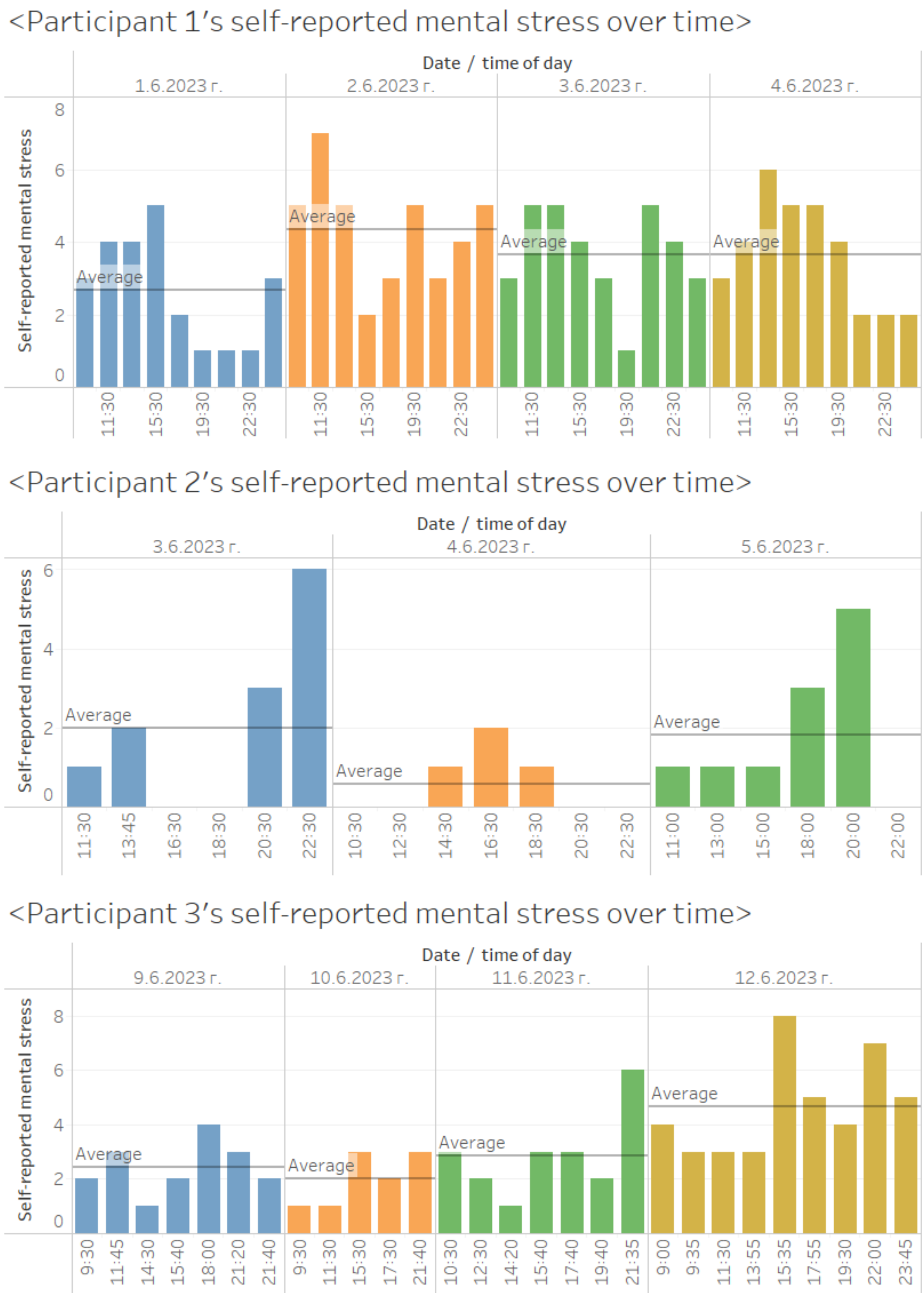

Figure 13. Distribution of self-reported mental stress levels for the three participants over the day

6.3 Preliminary analysis of HRV

After the first self-reported measure (mental stress) was investigated, it was time to move to a measured one – HRV. As mentioned in the previous chapter, Fitbit's Web API provides RMSSD data only for the night but for the aims of this research the HRV data for the duration of the day is also important. According to the procedure described previously an approximation of RMSSD was acquired. Even though the description of the json requests for heart rate indicates that a detail level (having data every so often) of 1 second is possible, it turns out that when requesting 1 second intervals the output is given for every 10-15 seconds. Due to that the intervals at which the RMSSD estimation is calculated became slightly uneven – Fitbit's Web API provides data for every 5 round minutes, but in the case of the calculated values it was made such that once a continuous interval of 5 minutes is reached an RMSSD value is calculated (e.g. the first calculated interval of 01.06.2023 for P1's data is at 00:05:17). Upon comparison between the results of the method used and the data as acquired by the API it was discovered that the two differ quite significantly as shown on the graph below (Figure 14). The plot of the data as provided by Fitbit shows not only higher values but also more outspoken peaks. Given the fact that the scales differ slightly, a correlation coefficient cannot be calculated but as per the method of visual inspection described in the beginning of this chapter one can tell that it would be low. Additionally, Umetani et al. [64] determined a 43+-19 value (mean value +- one standard deviation) for RMSSD for people aged 20-29. From the calculated RMSSD about 59,2 % are within this range, while only about 22.55% of the RMSSD values as given by Fitbit fall within this range. It was expected that there would be some (small) discrepancy due to the fact that the calculated RMSSD is an estimation. For other days and participants, this difference was also evident. Because of how different the datasets are, it was decided that only the scale of the calculated RMSSD will be used in further analysis.

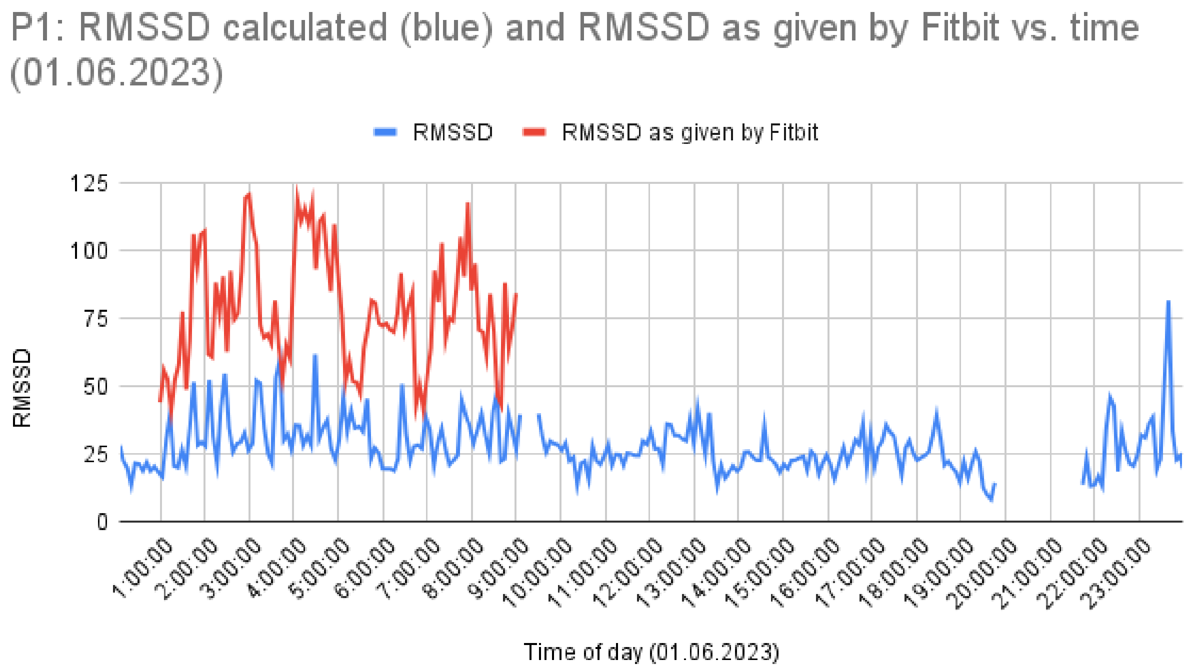

Figure 14. P1: RMSSD calculated (blue) and RMSSD as given by Fitbit's Web API vs time of day (01.06.2023)

6.4 HRV and self-reported mental stress

After the preliminary analysis of the integrity of the HRV data was done, the RMSSD value was exported to a csv file, the “Text to columns” function of MS Excel was used to make the data workable and the self-reported mental stress values were put together with that. Using the “QUARTILE” function of MS Excel the first and third quartiles were identified and according to the “1.5 * IQR” method, potential outliers were identified. The outliers were highlighted through conditional formatting and were dealt with manually. Some of them were removed (because it was evident that they were faulty values captured when the wearable was not being worn) and others were swapped for the lower/higher bound of the 95% confidence interval or other appropriate values depending on the situation.

The self-reported mental stress values were distributed to approximately fit the timestamps from the HRV data. That was done so that the correlation coefficient between the values could be computed. Orsila et al. [20] state that lower RMSSD values indicate higher stress, thus a positive change in stress levels would result in a negative change in RMSSD and the other way around. Still, that does not mean that only and solely a negative correlation coefficient would prove that indeed there is an explicit relationship in the case of the current study. To explore the connection, periods of time are chosen such that there is a change in the self-reported mental stress value (e.g. on 01.06.2023, P1 reported mental stress levels of 4 between 09:30 and 13:30 and mental stress levels of 5 between 13:30 and 15:30). The occasions of negative correlations are more and on average are stronger than the positive correlations as depicted on the dashboard in Figure 15 (colours in the dashboard are for the sake of distinguishing the different days easily). Such negative correlations could be a sign that the participants' bodies are coping well with the mental stress they are experiencing. In such cases, when the correlation is positive, it is important to think about how and if it is a good idea to provide certain suggestions/aids such that the user starts coping better. On the other hand, participants might have under-/over- estimated their stress levels or that there were external factors involved for the given time periods. In this case, it could be useful to prompt the user for more input in order to get a better understanding of the situation. As it can be seen especially in the case of participant 3 for 10.06.2023 there is some missing data. The participant reported their stress levels but they were not wearing the smartwatch and as such correlation coefficients between RMSSD and self-reported mental stress could not be computed for more than one period of this day.

Figure 15. P1: Correlation coefficient for RMSSD and Self-reported mental stress presented by day and time period

6.5 Sleep metrics and self-reported mental stress

Once the analysis between HRV and self-reported mental stress was carried out, the sleep metrics and self-reported mental stress were looked into. Through Fitbit's Web API, were acquired the durations of sleep, the timestamps at which the participant has gone from one sleep stage to the next and the sleep score efficiencies as provided by Fitbit. Through the Python script, the periods between the timestamps of the sleep stages were filled out such that for every minute of the night there is an indication of the sleep stage. This was exported to a csv file, the "Text to columns" function was used to make the data workable and the self-reported stress values were put together with that for each day.

As mentioned in Section 2.1.3 sleep quality is a complex measure relying on one's self-satisfaction with their sleep experience. It has to be noted that this self-satisfaction has to be considered carefully. This is because people's judgement might be disrupted and somewhat poor as mentioned in Section 6.1 due to the fact that they have just woken up. Even though participants in the study were not specifically prompted to evaluate all the different aspects of their sleep they were asked to evaluate their overall sleep experience. As such it is important to gather a better understanding of how it relates to other aspects. One such aspect is the duration of the sleep. Here it is important to mention that Participant 3 failed to wear the smartwatch on the night of 11.06.2023. The duration of the sleep and the overall self-reported satisfaction with the sleep experience were compared with each other for every participant for each day on the dashboard in Figure 16. For Participant 1 the overall self-reported satisfaction with the sleep experience (green squares) and the sleep duration (yellow circles) increase/decrease together, contrary to participants 2 and 3 in that regard. This shows that the duration of the sleep for a given day cannot speak for the overall sleep quality. This becomes especially evident when observing the graph of Participant 2. There, they reported worst overall sleep experience for the days they slept more during the study. As such, the measures are analysed further.

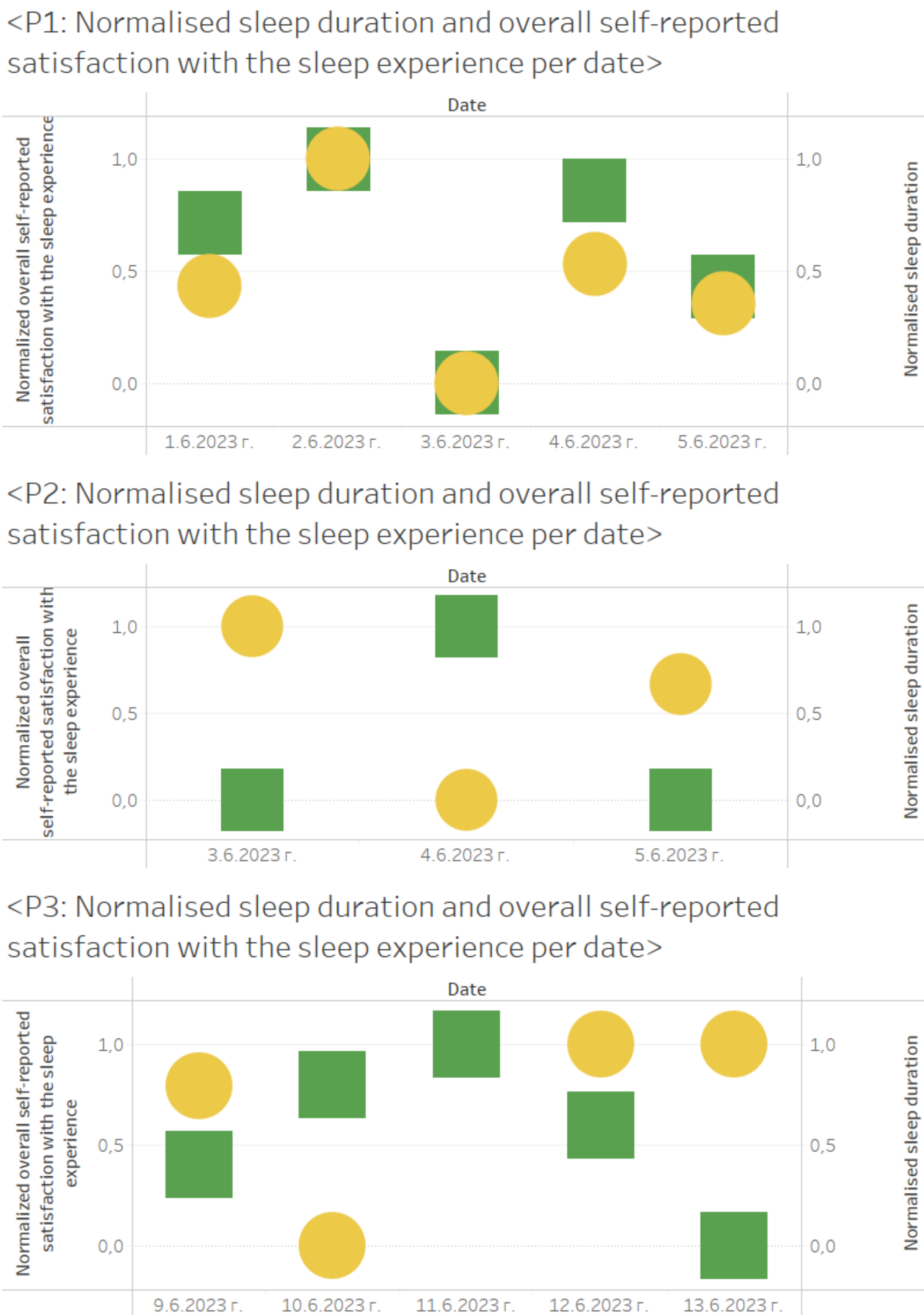

Figure 16. P1, P2 and P3: Normalised sleep duration (in yellow) and overall self-reported satisfaction with the sleep experience (in green) per date

To further expand on the analysis of sleep metrics, next the sleep stages were explored. A popular metric for quality sleep (not to be mistaken with the sleep quality as defined previously) are the cycles of the stages of the sleep. Patel et al. [81] mention that, per night, a person naturally goes through 4-6 cycles containing each stage. Even though Fitbit's Web API does not provide direct information about these cycles they can be calculated from the stages as provided. The cycles, though, are rather complex to analyse on their own as "time spent in each sleep stage may become altered by depression, aging, traumatic brain injuries, medications, and circadian rhythm disorders" as stated by Patel et al. [81] as such they were not accounted for in the current study. On the other hand, it was hypothesised that the distribution of the sleep stages could be related to other factors.

The distribution of the sleep stages per night for every participant was graphed through pie charts (figures 17, 18 and 19). Additionally, information about the duration of the sleep, the self-reported overall satisfaction with the sleep, the sleep efficiency given by Fitbit and the average self-reported mental stress for the day were added on top of each chart to investigate all of them at one place (see figures 17, 18 and 19). Upon investigation a few details make an impression. For Participants 2: the amount of light sleep and the duration of the sleep increase/decrease together. For Participant 3: the amount of REM increases/decreases with the duration of the sleep, the proportion of deep sleep on 10.06 is rather big, given that the duration of the sleep was short, on the 10.06 and 13.06 the proportion of deep sleep is approximately the same even though the duration and the overall self-reported satisfaction with the sleep experience are very different, and last, the amount of light sleep and the average self-reported mental stress increase/decrease together. As established (from the description and figures 17, 18 and 19 the data is rather complex, the datasets, are pretty small and include data from only 3 participants and 3-4 nights each and no definitive conclusions can be made (even such that are solely based on the data available).

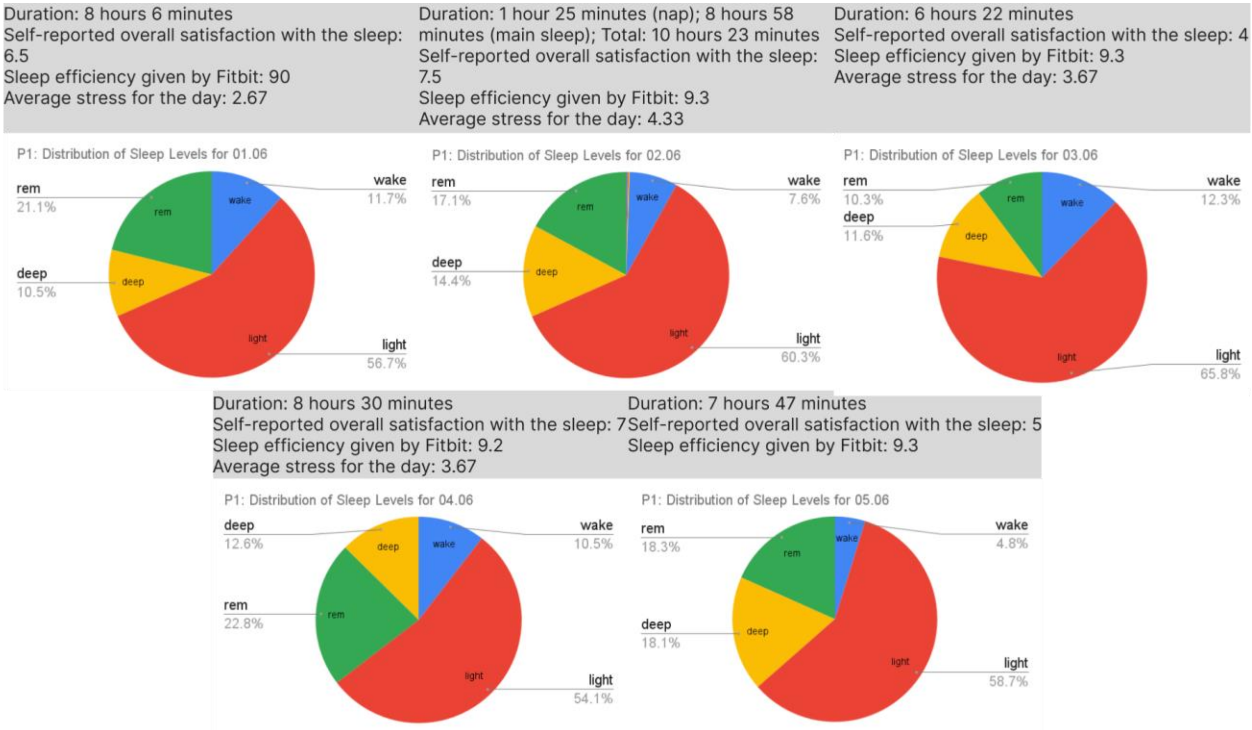

Figure 17. P1: Distributions of sleep stages together with duration of the sleep, the self-reported overall satisfaction with the sleep, the sleep efficiency given by Fitbit and the average self-reported mental stress for the day

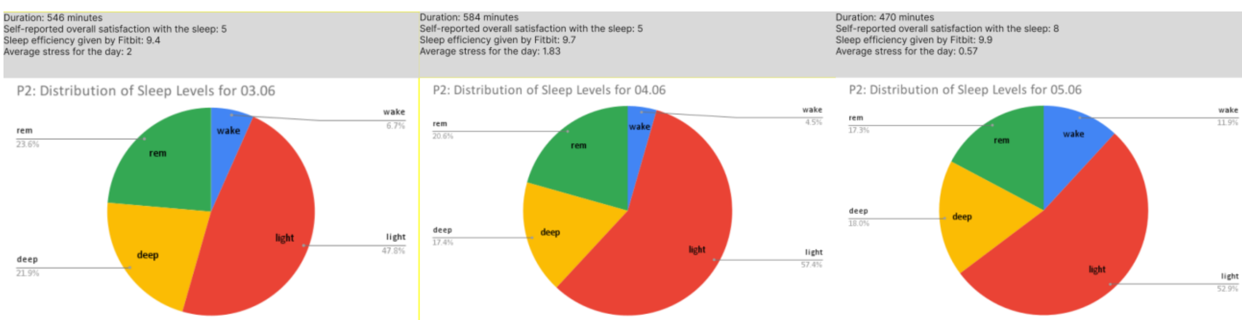

Figure 18. P2: Distributions of sleep stages together with duration of the sleep, the self-reported overall satisfaction with the sleep, the sleep efficiency given by Fitbit and the average self-reported mental stress for the day

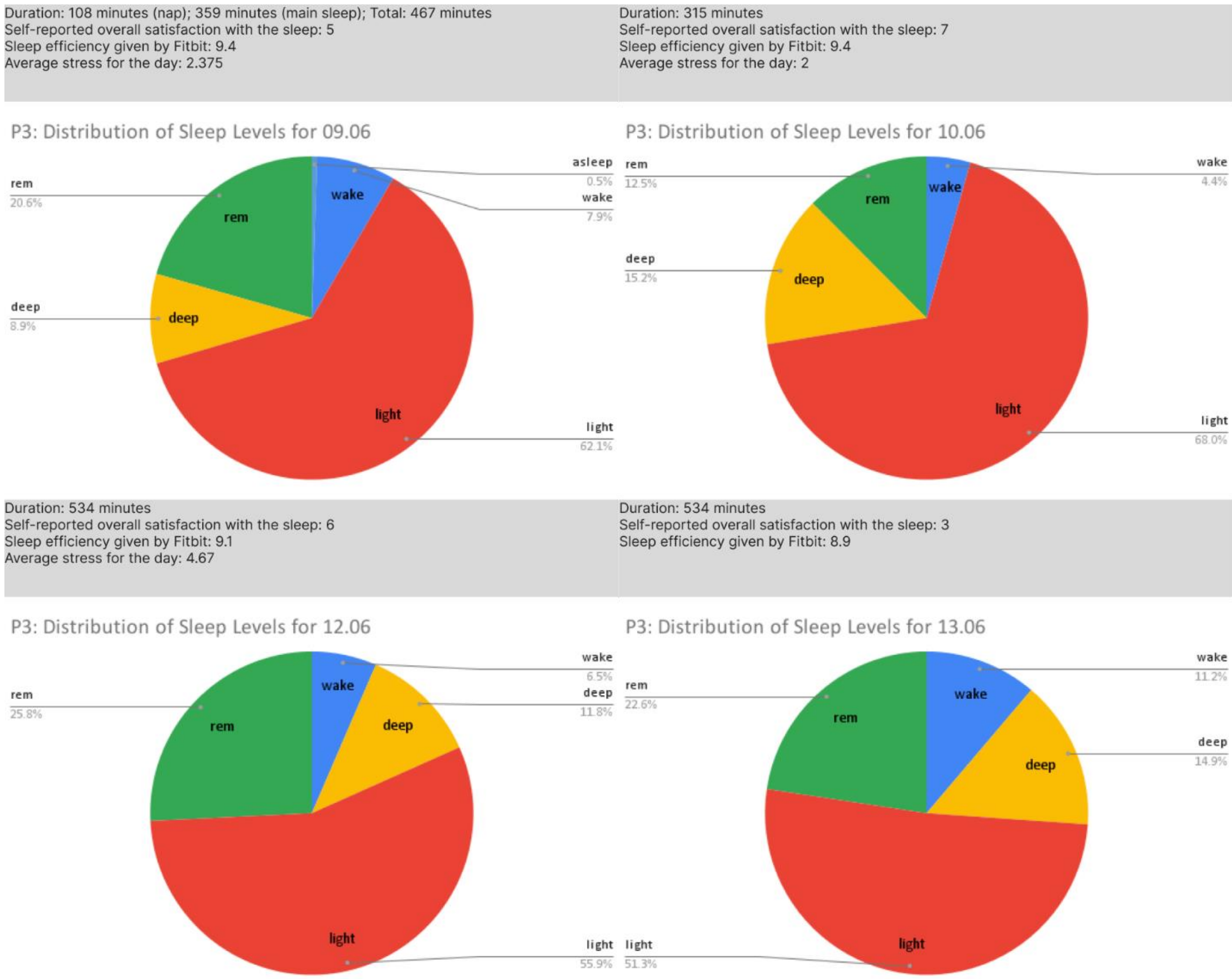

Figure 19. P3: Distributions of sleep stages together with duration of the sleep, the self-reported overall satisfaction with the sleep, the sleep efficiency given by Fitbit and the average self-reported mental stress for the day

As can be observed in Figures 16 and 18, for dates 02.06 and 09.06 respectively, there are additional "awake" and "asleep" stages annotated which form very small parts of the overall distribution of the sleep stages for those days. These occurrences are due to the fact that on these dates participants 1 and 3 took naps and the sleep log provides their duration as well as the stages "awake", "restless" and "asleep" which follow one after the other in a matter of 1-2 minutes. Fitbit tracks naps longer than 1 hour [77] while sleep stages are provided for periods of sleep longer than 3 hours [70]. Naps have been shown to have stress-reducing effects [75]. Due to the small amount of such during the current study no such effects can be determined and the naps duration was summed with the duration of the "main" sleep for the day to be used in the analyses.

It was also hypothesised that there might be a relationship between the distribution of time spent in certain stage(s) of sleep throughout the night and the total duration of sleep the average stress experienced throughout the next/previous day or the overall self-reported satisfaction with the sleep experience. None of these hypotheses though could be proven due to the small amounts of data. Even though for every participant they were tested numerically and in some cases there was a high correlation coefficient between the tested variables it is more likely that this is rather coincidental and a definitive conclusion cannot be made. Another comparison that was made was the one between self-reported mental stress and the self-reported satisfaction with the sleep experience. This analysis did not live up to the initial expectations which were that there will either be a pattern between how well the person believes they have slept (their self-reported overall satisfaction with their sleep) and the mental stress levels they experience throughout the day or a pattern when it comes to the self-reported overall satisfaction with the sleep in relation to the mental stress levels reported the day before.

Another point to mention as part of the sleep metrics is the sleep efficiency score provided by Fitbit. It was tested numerically for relations to the other variables and also included above every pie chart on figures 17, 18 and 19 to investigate if there will be something that makes an impression together with the visual, but nothing showed up/was proven. It is not clear also what exactly this score consists of. A number of formulas (combining sleep variables in different ways) can be found in the community forums of Fitbit [73] but none of them would return the correct result. Additionally, the Sleep efficiency score was found to be different from the standard measure of sleep efficiency "commonly defined as the ratio of total sleep time (TST) to time in bed (TIB)" as described in the work of Reed and Sacco [74]. This lack of insight questions the trustworthiness of the variable. On the other hand, Fitbit could be intentionally refraining from providing information on the variable to remain ahead of the competition. In any case, it was deemed too vague to be discussed in the analyses.

6.5 Conclusions

After processing and analysing the data a number of conclusions could be drawn to address the main research question and the first research sub-question (as defined at the beginning of chapter 4). When it comes to mental stress by itself, it was previously mentioned, that it is a rather complex matter. As shown in Section 5.1 it is highly important to consider people's schedules, and personal preferences regarding when they start their days, when they end them and how they spread out and utilize their schedules. This would bring more insight as to when certain changes could occur and what their magnitude could be. When it comes to RMSSD (as a measure of HRV) in relation to mental stress the data showed a rather promising negative correlation among all participants. As for sleep quality and sleep metrics, the data showed that the overall self-reported satisfaction with one's sleep can heavily rely on the duration of their sleep but also not at all, which confirms the initial expectation that sleep quality is a complex multidimensional measure which is hard to be interpreted without input from the user. As a whole, the sleep metrics did not show much indication of their relationship with participants' mental stress levels directly.

Chapter 7 – Discussion, Limitations and Future work

After the evaluation of the research was laid out in the previous chapter in this chapter certain the findings and some decisions will be discussed in order to provide a better overview of the overall completion of the project. This chapter will consist of 3 sections: Research questions, Limitations and Suggestions for future research.

The current research project aimed to investigate how can wearables and their functionality be employed so that through known indicators of stress a connection could be made with mental stress in young people. Wearables are highly accessible (and with increasing popularity) and their developers and producers come up with more and more functionalities, many of which are related to bodily functions. Some of these bodily functions have been proven scientifically to be indicators of stress. Many wearable companies use them as such but they do not indicate the type of stress which their devices and applications detect which is somewhat deceiving to the users. Since mental stress is one thing scientists and media have drawn attention to lately, it was interesting to see how in reality wearables could be used to gather data on known stress indicators, take into account users' preferences and the relationships in hand and use them to potentially develop an interface which could present the users with the right data for an application which determines mental stress.

7.1 Research questions

In terms of the main research question ("How can heart rate variability and sleep quality be used in order to determine mental stress?") it could be said that RMSSD (as a measure of HRV) is a rather suitable indicator for mental stress as it showed a promising negative correlation with mental stress. Sleep quality, however, and sleep metrics did not show convincing results but it is believed that with further investigation those measures could come in useful.

The next point to mention is related to the first research sub-question - "Can a relationship be identified between the two indicators - heart rate variability and sleep quality?". Given that Fitbit uses HRV to detect sleep stages [70] and the fact that their RMSSD value was disregarded from the research, comparing sleep stages and calculated RMSSD data does not make sense. As such the sleep stages were taken as a given.

The second research sub-question ("What suggestions can be given to university students in order for them to adjust their schedule in an optimal way to reduce stress levels?") was not investigated as the other two research questions did not produce the initially expected results and the study became more complex. It is believed, though, that this research question has a lot of potential since as stated in Section 6.2 schedules are an important aspect of the analysis and understanding of mental stress. As such it is important to mention that as it was laid out in Chapter 4, participants were asked for a rough schedule of their activities for the days of their participation in the data collection. The participants could not provide such schedule in advance and also struggled to reproduce it a few days after the data collection. Having such schedules could have induced different results and/or a better understanding.

7.2 Limitations

In Chapter 4, the procedure for the current research could be summed up in three phases – data collection, an interview with the users (after analysis of the data) and an evaluation of a product, built based on said analysis and the interview. As mentioned earlier the data gathered during the data collection phase is extensive and the variables are not perfectly suited to be compared with each other easily or directly. Due to that the analysis took much more time and effort and had a rather explorative nature rather than a definitive one. This led to an inability to perform the interview and design of a prototype as was the initial plan. Even so, this research produced interesting findings, most of which were unexpected. One such finding was how not only in theory but also in practice, Fitbit (as an example of a well-established company for wearables) provides a lot of information but it is only superficial. Fitbit states that HRV is being calculated. Upon investigation, though, through the data provided by the Fitbit Web API, it turns out that only some HRV measures are taken into account and can be accessed but with no apparent reasoning. For the aims of the research HRV data (particularly RMSSD to match with what is available) was needed for the day hours (Fitbit Web API provides HRV data only for when the user is asleep for the night). This led to investigating a way to calculate it through other variables provided and as such an RMSSD estimation was calculated from heart rate. Upon comparison between the calculated measure and the one acquired by the API, a big difference was discovered. This could have been due to the fact that the RMSSD calculated was an estimation, but the magnitude of the difference raises a question if there could be other factors involved.

The next important aspect to mention is related to the RMSSD measure. As mentioned in Section 5.1 the calculated for the purpose of this study RMSSD values are an estimation from using heart rate measurements at given times. The method of the calculation is not solely based on a formula but follows a line of reasoning and conclusion drawn from several sources and it was deemed sufficient for the purposes of the research. This is a limitation to the study because if a different method had been used there could have been different results (especially when it comes to the correlation coefficient that was calculated between RMSSD and self-reported mental stress levels). Even so, the fact, that the range of the calculated RMSSD was closer to the range found in literature than the range of the RMSSD values given by Fitbit (see Section 6.3), cannot be disregarded.

As mentioned in Section 6.4 the effect of napping (as a form of sleep) on stress could not be investigated and their duration was just summed with the “main” sleep duration for the day. This certainly acts as a limitation to study as naps could have an effect on one’s sleep quality/self-reported satisfaction with their sleep experience. Given that researchers continue to make new findings in regards to different aspects of napping it could be interesting to see how wearables and their ability to capture naps’ duration and timing can contribute to making further progress when it comes to sleep quality and its relationship with (mental) stress.

7.3 Suggestions for Future research

In Chapter 5 it was mentioned that the current research had to be somewhat downscaled in comparison to the initial plan laid out in Chapter 4. That was mainly due to the complexity of the data acquired. It was hard to be compared, explored and processed. It contained self-reported as well as measured variables and different scales. Having this in mind as well as the point discussed above, there are a few suggestions for future research in the field of Wearables and Stress. First of all, a better understanding of wearables is needed. A considerable part of many of the most popular wearables’ functionality is a black box, and to fully utilize their potential, it is important to have a clear overview of the "what's", "why's", and "how's". Secondly, to come closer to detecting mental stress one should not rely solely on its levels but also on detailed information from the user. That will provide a good overview and reasoning for the possible changes and reactions of the human body that can be measured with wearables (potentially). Another suggestion would be to include the measure of Skin Conductance (as had been initially planned in the current study). This will provide a better overview of the overall functionality of the ANS as it could explain the balance between the sympathetic and parasympathetic nervous systems according to the mental stress levels and their changes. The last suggestion for future research would be to involve specialists in the field of Physiology as their input for the bodily signals and functions (especially sleep) would help create better analysis and draw appropriate concrete conclusions.

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Appendix

Appendix A. Python script for acquiring HRV data and Heart Rate data through Fitbit Web API

```
import requests
from datetime import datetime, timedelta
import math
import csv

access_token = ""

header = {'Authorization': 'Bearer {}'.format(access_token)}

time_value_list = []
csv_filename = "HRV_data.csv"
heart_rates_at_every_minute = []
values_list = []

RR_interval_duration_list = []
RR_interval_list = []

num_intervals = len(RR_interval_list)
num_full_sets = num_intervals // 5

url_heart_rate = f"https://api.fitbit.com/1/user/-/activities/heart/date/2023-06-01/1d/1sec.json"
url_HRV = f"https://api.fitbit.com/1/user/-/hrv/date/2023-06-01/all.json"

raw_heart_rate_data = requests.get(url_heart_rate, headers=header).json()
print (raw_heart_rate_data)

given_times_list = []
heart_rates_at_given_time = []
RR_interval_list = []

for entry in raw_heart_rate_data['activities-heart']:
    date = entry['dateTime']

for entry in raw_heart_rate_data['activities-heart-intraday']['dataset']:
    # put dateTtime and heart rate values in variables
    timestamp = entry['time']

    heart_rate = entry['value']

    # print ("Heart rate at", self.timestamp, ": ", heart_rate)
    given_times_list.append(timestamp)
    heart_rates_at_given_time.append(heart_rate)
```

```
for r in range(len(heart_rates_at_given_time) - 1):
    RR_interval_duration = 60 / heart_rates_at_given_time[r]
    RR_interval_duration_list.append(RR_interval_duration)

    if r >= 1:
        RR_interval = RR_interval_duration_list[r] - RR_interval_duration_list[r - 1]
        RR_interval_list.append(RR_interval)

time_and_RR_interval = []
for r in range(len(RR_interval_list)):

    # given_times_list[r] = given_times_list[r] + 'T' + date
    time_and_RR_interval.append((given_times_list[r], RR_interval_list[r]))

print (time_and_RR_interval)

r = 0
RMSSD_list = []
rms_time = []
prev_len = 0
while r < len(time_and_RR_interval):
    subsets_list = []
    five_minute_subset = [time_and_RR_interval[r + i][0] for i in range(1)]
    time_difference = timedelta(minutes=0)
    starting_timestamp = datetime.strptime(five_minute_subset[0], "%H:%M:%S")
    rr_interval_subset = []
    i = 0

    while time_difference < timedelta(minutes=5):
        if r + i < len(time_and_RR_interval):
            five_minute_subset.append(time_and_RR_interval[r + i][0])
            rr_interval_subset.append(time_and_RR_interval[r + i][1])
            last_timestamp = datetime.strptime(five_minute_subset[len(five_minute_subset)-1], "%H:%M:%S")
            time_difference = last_timestamp - starting_timestamp
            subsets_list.append((five_minute_subset, rr_interval_subset))
            i = i + 1
        else:
            break

    rms_value = math.sqrt(sum(rr_interval_subset[j] ** 2 for j in range(len(rr_interval_subset))) /
len(rr_interval_subset))

    # convert from seconds to miliseconds to match the RMSSD in the HRV module
    RMSSD = rms_value * 1000
    print('RMSSD value in ms at', five_minute_subset[len(five_minute_subset)-1], 'of', date, ':', RMSSD)
    rms_time.append (five_minute_subset[len(five_minute_subset)-1])

    RMSSD_list.append(RMSSD)

    r = r + i + 1


# ---------------------------------------------------------------------------------------------

for entry in raw_heart_rate_data['activities-heart']:
    date = entry['dateTime']
```

```
for entry in raw_heart_rate_data['activities-heart-intraday']['dataset']:
    # put dateTtime and heart rate values in variables
    timestamp = entry['time']

    heart_rate = entry['value']

raw_HRV_data = requests.get(url_HRV, headers=header).json()

minutes_list = [item['minute'] for item in raw_HRV_data['hrv'][0]['minutes']]
formatted_time_list = []
HRV_date = None

for minute in minutes_list:
    # Convert string to datetime object
    dt = datetime.strptime(minute, '%Y-%m-%dT%H:%M:%S.%f')

    # Extract the time part in hh:mm:ss format
    formatted_time = dt.strftime('%H:%M:%S')

    # Append the formatted time to the list
    formatted_time_list.append(formatted_time)

    # Extract the date if it hasn't been extracted yet
    if HRV_date is None:
        HRV_date = dt.date()

rmssd_list = [item['value']['rmssd'] for item in raw_HRV_data['hrv'][0]['minutes']]
coverage_list = [item['value']['coverage'] for item in raw_HRV_data['hrv'][0]['minutes']]
hf_list = [item['value']['hf'] for item in raw_HRV_data['hrv'][0]['minutes']]
lf_list = [item['value']['lf'] for item in raw_HRV_data['hrv'][0]['minutes']]

for i in range(len(rmssd_list)):
    time = formatted_time_list[i]
    RMSSD = rmssd_list[i]
    print('RMSSD value in ms at', time, 'of', date, ':', RMSSD)

# Creates a csv file with the RMSSD values and their corresponding times
with open(csv_filename, mode='w', newline='') as file:
    writer = csv.writer(file)
    writer.writerow(['Time', 'RMSSD'])
    for r in range(len(rms_time)):
        # rms_time[r] = rms_time[r] + 'T' + date
        writer.writerow((rms_time[r], RMSSD_list[r]))
    for i in range(len(rmssd_list)):
        writer.writerow((formatted_time_list[i], rmssd_list[i]))
    print("The CSV file has been writen")
```

Appendix B. Python script for acquiring Sleep data through Fitbit Web API

```
import requests
import csv

access_token = ""
header = {'Authorization': 'Bearer {}'.format(access_token)}
date = "2023-05-20"
```

```
raw_sleep_data = requests.get("https://api.fitbit.com/1.2/user/-/sleep/date/2023-06-03.json", headers=header).json()

print (raw_sleep_data)

# Access the 'sleep' list from the 'raw_sleep_data' dictionary
sleep_data = raw_sleep_data['sleep']

csv_filename = "sleep_data_02.06.csv"

with open(csv_filename, mode='w', newline='') as file:
    writer = csv.writer(file)
    writer.writerow(['Time', 'Sleep Level'])

    for item in sleep_data:
        efficiency = item['efficiency']
        levels_data = item['levels']
        data_list = levels_data['data']

        for i in range(len(data_list)):
            date = item['dateOfSleep']
            time = data_list[i]['dateTime']
            level = data_list[i]['level']

            writer.writerow([time, level])

            if i < len(data_list) - 1:
                curr_time = data_list[i]['dateTime']
                next_time = data_list[i+1]['dateTime']

                curr_hour = int(curr_time[11:13])
                curr_minutes = int(curr_time[14:16])
                next_hour = int(next_time[11:13])
                next_minutes = int(next_time[14:16])

                while curr_hour < next_hour or (curr_hour == next_hour and curr_minutes < next_minutes):
                    curr_minutes += 1
                    if curr_minutes == 60:
                        curr_minutes = 0
                        curr_hour += 1

                    filled_time = curr_time[:11] + str(curr_hour).zfill(2) + ':' + str(curr_minutes).zfill(2) + curr_time[16:]
                    if filled_time != next_time:
                        writer.writerow([filled_time, level])

                    curr_time = filled_time

    print("The efficiency of the sleep was:", efficiency)

print(f"The sleep data has been written to the file '{csv_filename}'.")
```

Appendix C. Ethical documents

Consent Form for Wearables and Stress

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	Ye s	No
Taking part in the study		
I have read and understood the study information dated [DD/MM/YYYY], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	□	□
I understand that taking part in the study involves wearing a smart watch which captures my HRV data and sleep metrics, filling out forms on a daily basis, participating in an interview at a later stage as well as evaluating the realisation of the product/prototype	□	□
Use of the information in the study		
I understand that information I provide will be used for a Bachelor’s thesis report	□	□
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	□	□
I agree that my information can be quoted in research outputs	□	□
I agree to joint copyright of the my daily logs to Stefan Hristov	□	□
Consent to be Audio Recorded		
I agree to be audio recorded. Yes/no	□	□
Future use and reuse of the information by others		
I give permission for the anonymised transcript of the interview to be archived in 4TU data repository so it can be used for future research and learning.	□	□

Signatures

_______________________ _______________________ _________

Name of participant

Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ ____________________ ________

Researcher name Signature Date

Study contact details for further information:

Stefan Hristov, s.hristov-1@student.utwente.nl

USER STUDY INFORMATION BROCHURE

Title of research project: Gathering data for exploration of the connection(s) between HRV, sleep quality and stress via the use of a wearable to build an interface which represents it and allows the user to be informed

Dear participant,

I would like to invite you to take part in a user research study on wearables used for stress tracking. Before you make a decision on whether to participate, you need to understand why the research is being done and what it would involve for you. Please take time to read the following information thoroughly. Ask questions if anything you read is not clear or if you would like more information. Take your time to decide whether or not to take part.

1. **Study Duration**

Phase 1 of the study will last at most **5 days**. Phases 2 will last up to **30 minutes** with each participant. Phase 3 will last at most **1 day.**

2. **Study Nature**

Phase 1: The overall aim of Phase 1 is to gather HRV and sleep metrics data which then to be connected to self-reported stress levels as well as potential stressful situations in accordance to the activities carried out during the study. You will be asked to wear a smart watch during 2-3 working days and the weekend directly following/preceding, as much as possible, carry out your days as you normally would and fill out forms daily. In the forms you will be asked to rate your sleep experience every morning and rate your stress levels a number of times per day. Additionally, you will be asked to provide the researcher with your rough schedule/planning for the time of the study and to log any unusual occurrences (strenuous activities, being spooked/scared, etc.).

Phase 2: After the data has been analysed you will be invited to an interview and inquired about your overall experience (how did you feel wearing a wearable, how did you feel about answering questions daily, etc.). Additionally, you will be asked to comment on/evaluate different aspects of the interface which will be the result of your answers and the analysis of the information gathered during Phase 1.

Phase 3: You will be invited to interact with the interface and to evaluate its realisation based on a System Usability Scale as well as other concrete questions/topics related to your opinion/answers in Phase 2. Please note that a Wizard of Oz method might be used to present you with (live) data through the interface.

The study is part of a Bachelor's graduation project as part of Creative Technology at the University of Twente. The results of the study will be included in the final thesis report.

3. Voluntary participation

Participation in this study is completely voluntary. Should you decide to not participate you have no obligation to give any reasoning about such a decision. Even if you give your consent now, you can withdraw this consent at any time without having to give an explanation.

4. Possible Advantages and Disadvantages

The advantage of this research is that it will make you think about your stress levels and how (well) you sleep. I hope to support students with their stress management. You can start learning about yours and you will help me with my research.

5. Confidentiality of personal details and access by third parties

The information collected in this study will be treated confidentially. All data will be handled abiding by the regulations of secure storage and processing as outlined in the European Union's General Data Protection Regulation (GDPR). Personal details collected during this study, as well as the transcript resulting from the audio recording, will be anonymized via participant numbers. Only these numbers will be used for study documentation and in the final report of the project. The person corresponding to a code number can only be identified by the main researchers and potentially by the project supervisors. The audio recording and the anonymized transcripts will be stored on a hard drive which will be kept in a safe location for the duration of the study. The recording will be deleted, but the anonymized transcripts will be stored on

6. Who should you contact for further information?

For any further information you can contact one of the researchers:

s.hristov-1@student.utwente.nl

If you have questions about your rights as a research participant or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the project supervisor.

Additionally, you can contact the Secretary of the Ethics Committee of the Faculty of Electrical Engineering, Mathematics and Computer Science at the University of Twente through ethicscommittee-cis@utwente.nl.

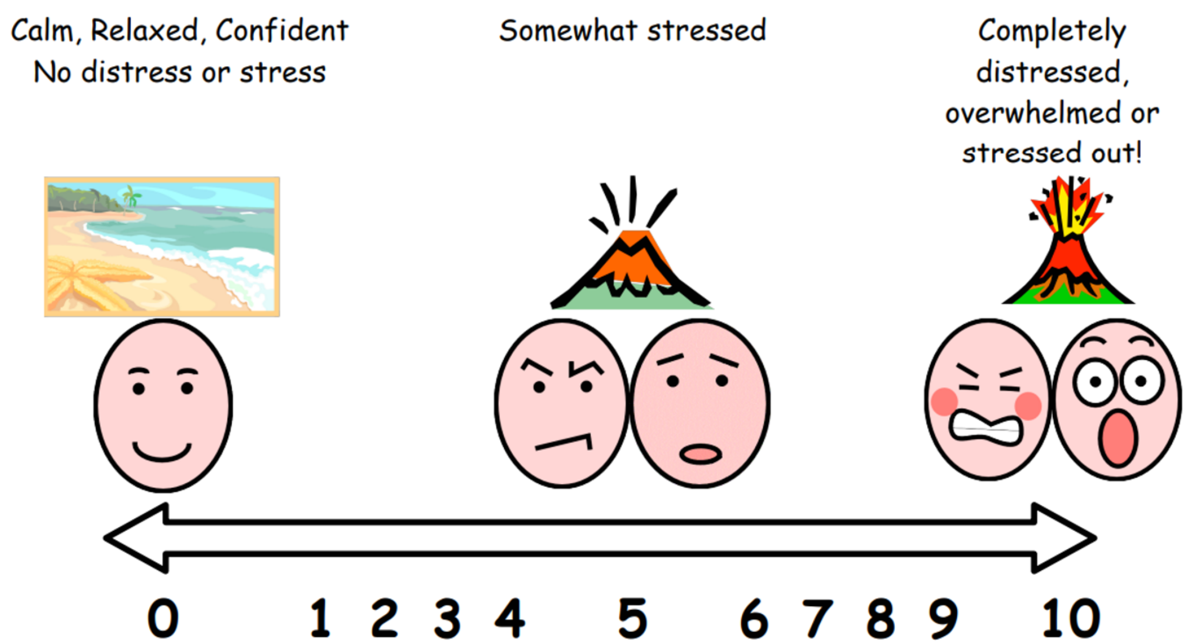
Appendix D. Daily form

Instructions: Half an hour after you wake up please log your sleep and your first mental stress rating:

Time that I woke up today: _____:_____. The date today is: ____/06/2023

On the scale of 0-10 I would rate my overall sleep experience with a: _____

Instructions: (Approximately) Every two hours please reflect on what were your mental stress levels for that period. If you are not sure how to evaluate the past two hours give a rating for the moment of filling in and leave a start next to the rating.



According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____

According to the scale above my mental stress level at ____:_____ for the past two hours was _____