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Measuring the Effects of Cognitive Stress and Relaxation Using a Wearable Smart Ring

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ABSTRACT

Prolonged stress is known to be a risk factor for various kinds of diseases, such as cardiovascular diseases. If stress could be easily measured, it would enable monitoring of stress and help people make better choices to achieve a healthier lifestyle. In this study, a polysomnography system as well as a wearable smart ring were used to measure the responses of central and autonomic nervous systems from ten healthy test subjects (five male and five female), aged 23-26. The responses were measured in two conditions: cognitive stress induced by a mental calculation task and relaxation induced by a focused attention meditation exercise.

Power spectral densities of two electroencephalography frequency bands, alpha and beta, were calculated to represent the central nervous system response. The autonomic nervous system response was measured using heart rate, heart rate variability and peripheral (finger) temperature. In cognitive stress, alpha and beta bands both showed higher activity, increasing by 53.26 % and 94.70 %, respectively. Heart rate also increased by 19.33 %, while heart rate variability decreased by 25.65 % and peripheral temperature change was 0.77 ℃ lower.

Results show that the changes in autonomic nervous system responses acquired by the smart ring correlate with the changes in central nervous system responses acquired by the polysomnography system. This suggests that a smart ring could be used for an indirect measurement of human stress level. Follow-up studies with larger sample sizes are needed to confirm the findings of this study and to determine the most suitable features for representation of human stress level.

Keywords: central nervous system, autonomic nervous system, stress, cognitive, relaxation, meditation, electroencephalography, photoplethysmography, heart rate, heart rate variability, body temperature, wearables

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TIIVISTELMÄ

Pitkittynyt stressi toimii riskitekijänä lukuisille sairauksille, kuten sydän- ja verisuonitaudeille. Stressin vaivaton mittaaminen mahdollistaisi stressitason seuraamisen, mikä vuorostaan auttaisi ihmisiä tekemään parempia valintoja terveellisemmän elämäntyylin puolesta. Tässä tutkimuksessa käytettiin polysomnografialaitteistoa sekä puettavaa älysormusta keskushermoston ja autonomisen hermoston vasteiden mittaamiseen kymmeneltä terveeltä koehenkilöltä (viisi miestä ja viisi naista), iältään 23-26. Vasteet mitattiin kahdessa tilassa: päässälaskutehtävän aikaansaamassa kognitiivisessa stressissä sekä hengitykseen keskittyvän meditaatioharjoituksen aikaansaamassa rentoutumisessa.

Kahdelle elektroenkefalografian taajuuskaistalle, alfalle ja beetalle, laskettiin tehon spektritiheydet kuvastamaan keskushermoston vastetta. Lisäksi laskettiin syke, sykevälivaihtelu sekä ääreislämpötila (sormen lämpötila) kuvastamaan autonomisen hermoston vastetta. Kognitiivisessa stressissä sekä alfa- että beetakaistan aktiivisuus kasvoi, alfalla 53,26 % ja beetalla 94,70 %. Myös syke nousi 19,33 %, kun taas sykevälivaihtelu pieneni 25,65 % ja ääreislämpötilan muutos oli 0,77 ℃ pienempi.

Tulokset osoittavat, että älysormuksella mitatut autonomisen hermoston vasteen muutokset korreloivat polysomnografialaitteistolla mitattujen keskushermoston vasteen muutosten kanssa. Tämä antaa ymmärtää, että älysormusta voitaisiin käyttää ihmisen stressitason epäsuoraan mittaamiseen. Suuremman kokoluokan jatkotutkimuksia tarvitaan varmistamaan tämän tutkimuksen löydökset sekä määrittämään sopivimmat fysiologiset piirteet kuvastamaan ihmisen stressitasoa.

Avainsanat: keskushermosto, autonominen hermosto, stressi, kognitiivinen, rentoutuminen, meditaatio, elektroenkefalografia, fotopletysmografia, syke, sykevälivaihtelu, kehon lämpötila, puettavat

TABLE OF CONTENTS

FOREWORD

This thesis was requested by Oura Health and it serves as the final work of my Biomedical Engineering Master's degree. I truly appreciate this opportunity and although there have been ups and downs, it has been a pleasure working on this project. I would like to thank both my mentors, Olli Heikkinen (Oura Health) and Jukka Kortelainen (University of Oulu), for guiding me throughout this journey. I'm very thankful that even during more hectic times you still were able to read my drafts and show interest in this thesis. Additionally, I would like to thank my partner in measurements and a good friend of mine, Aleksi Rantanen (Oura Health), for showing me how to use all the devices and helping me to get through the measurements quite effortlessly. The measurement phase would have been quite a bit trickier without your support. Speaking of measurements, I would also like to thank my fellow students for participating in this study voluntarily. I appreciate your enthusiasm – for you to wear the electrodes not only for the daytime but for nighttime measurements as well, is truly not something to take granted for. Finally, I would like to thank my family and friends for giving me moral support over this period. It means a world to me.

Oulu, 27.3.2020

Tomi Honkanen

ABBREVIATIONS

ACTH	adrenocorticotropic hormone
ANOVA	analysis of variance
ANS	autonomic nervous system
CNS	central nervous system
CRH	corticotropin-releasing hormone
ECG	electrocardiogram/-graphy
EDA	electrodermal activity
EEG	electroencephalogram/-graphy
EMG	electromyogram/-graphy
EOG	eletrooculogram/-graphy
FIR	finite impulse response filter
HPA	hypothalamic-pituitary-adrenocortical axis
HR	heart rate
HRV	heart rate variability
IBI	interbeat interval
ICA	independent component analysis
IIR	infinite impulse response filter
PNS	parasympathetic nervous system
PPG	photoplethysmogram/-graphy
PSD	power spectral density
RIP	respiratory inductive plethysmography
RMSSD	root mean square of the successive R-R differences
SNS	sympathetic nervous system

1. INTRODUCTION

Acute stress is a part of our everyday lives. Human body responds to stressors, such as riding a bike to work in the morning or having to give a presentation in front of an audience, by increasing the heart rate and blood pressure, among other things. However, when acute stress becomes chronic, it also becomes a risk factor for diseases such as cardiovascular disease, diabetes, cancer and depression [1], [2], [3]. Short-term psychological stress can lead to myocardial infarction by disturbances in inflammatory, hemostatic and autonomic processes. In the long-term, chronic stress contributes to development of coronary heart disease and worsening the prognosis of these patients [2]. When the brain receives a stimulus that it characterizes as threatening, it launches a stress response by activating the sympathetic division of the autonomic nervous system (ANS) and by releasing cortisol from the adrenal glands [4]. Chronic high level of activity in this hypothalamic-pituitary-adrenocortical axis (HPA) can interfere with its control over important physiological systems, resulting in higher risk of disease [3]. Furthermore, stress causes increased vigilance and arousal, which can be detected in the central nervous system (CNS) level through electroencephalogram (EEG) [4]. If the stress level could be easily measured, it would enable monitoring of stress on a daily basis, which would help people make better choices to achieve a healthier lifestyle.

Stress measurement has been the topic in many studies, and several methods have been developed and tested for this exact purpose. For everyday use, wearables show great promise as they enable a more convenient measurement of stress. Usually these wearables measure the responses of the ANS, such as electrodermal activity (EDA), heart rate (HR) and heart rate variability (HRV), from locations such as around wrist [5], [6], [7], ankle [8] and from foot [9]. Photoplethysmography (PPG) is commonly used in wearables as it can be used for computation of HR and HRV, among other things [6], [8], [10]. Additionally, EEG has been utilized for stress measurement purposes. Wearable EEG headbands have been proposed, although they might not be as suitable for everyday use compared to the wearables measuring the ANS responses [11], [12]. Finally, combination of responses of both the ANS and CNS have been used in several studies [13], [14], [15], and even thermal imaging has been introduced for stress measurement [16]. For stress to be monitored day-to-day, the measurement needs to be comfortable and easy to use. This is where wearables, such as Oura smart ring, could prove to be useful.

In this study, outputs from the CNS and ANS were measured in a mentally stressful situation versus a relaxing situation, using a polysomnography system for the CNS and a smart ring for the ANS measurement. The objective was to compare the outputs in both phases and to find correlations between the two measurements, in order to evaluate the possible usage of a smart ring for indirect measurement of human stress level.

2. BACKGROUND

2.1. Central nervous system

The parts of the nervous system that are encased in bone, including brain and spinal cord, are referred to as the central nervous system (CNS) [4]. In all mammals, brain can be divided in three parts: the cerebrum, the cerebellum and the brain stem. The cerebrum is the largest part of the brain that is split down the middle into two cerebral hemispheres. Generally, right hemisphere receives sensations from, and controls movements of, the left side of the body, and vice versa. The cerebral cortex is arguably the most interesting part of the cerebrum: despite its large size and the fact that it can be measured using electroencephalogram (see chapter 2.2), it remains the most unknown part of the nervous system. Cerebellum, meaning “little brain” in Latin, is in fact notably smaller compared to the cerebrum but it still actually contains approximately as many neurons as both cerebral hemispheres combined. The cerebellum acts primarily as a movement control center, having extensive connections with the cerebrum and the spinal cord. Interestingly in contrast to the cerebral hemispheres, the left side of the cerebellum is concerned with movements of the left side of the body, and vice versa.

Brain stem is quite literally a stem from which both the cerebral hemispheres and the cerebellum sprout [4]. It is a conduit that relays information between the cerebrum, cerebellum and spinal cord. Additionally, the brain stem has an important task of regulating vital functions, such as breathing, consciousness, and controlling of body temperature. Indeed, while one can survive damage to the cerebrum and cerebellum, damage to the brain stem usually means rapid death. Finally, spinal cord is a pack of nerves that run inside the vertebral column and connects brain to the other parts of the body, such as skin and muscles. Damage to the spinal cord results in anesthesia in the skin as well as paralysis of the muscles in parts of the body that are caudal to the cut. The muscles are still functionable, but they lack the control of the brain. The spinal cord communicates with the body via the spinal nerves, which are discussed later in the autonomic nervous system chapter (see chapter 2.3).

Particularly interesting about the CNS from the perspective of this study is the previously mentioned cerebral cortex, more precisely the prefrontal area of it. The dorsolateral prefrontal cortex is responsible for planning approaches and sequences of behavior for achieving a goal [17]. These kind of thought processes require attention and inhibition of responses that are “counter-productive to the planning and execution of successful goal-directed behavior”. The dorsolateral prefrontal cortex is also associated with the so-called working memory, i.e. keeping events in mind for a short period of time. Indeed, the evolution of the prefrontal cortex is partly the reason why humans are so capable of such complex cognitive processes. However, it has also been implicated in various brain disorders such as attention deficit disorder, depression, PTSD and schizophrenia. Additionally, prefrontal cortex is vulnerable to stress, aging and Alzheimer’s disease.

When discussing about the physiology of stress, there is one area in the brain that cannot be ignored: the hypothalamus. Although it makes less than 1 % of the brain’s mass, the influence of the hypothalamus for the whole body is enormous [4]. To put it simply, the hypothalamus maintains homeostasis by regulating various factors in the body, including cardiovascular regulation, regulation of body water and temperature as well as gastrointestinal and feeding regulation, among other things. [18]. It sends signals in three directions: upward to many areas of the diencephalon and cerebrum, downward to the brain stem and through it to the peripheral nerves of the autonomic nervous system, as well as towards both the posterior and the anterior pituitary glands to control most of their secretory functions. During stress, the hypothalamus secretes corticotropin-releasing hormone (CRH), which triggers the release of adrenocorticotropic hormone (ACTH) from the anterior pituitary to the general circulation [4 (2)]. ACTH drifts via blood flow all the way to the adrenal gland on the top of the kidneys, where it again stimulates the release of cortisol from the adrenal cortex. This pathway is called the hypothalamic-pituitary-adrenal (HPA) axis. The released cortisol is a steroid hormone that acts throughout the body to prepare it for the stress, by e.g. mobilizing energy reserves and inhibiting immune system. It has also been shown that cortisol has significant effects on neuronal activity in the brain. However, the secretory function is not the only way the hypothalamus can send “stress signals” to the body. As mentioned earlier, hypothalamus is linked to the autonomic nervous system through the brain stem.

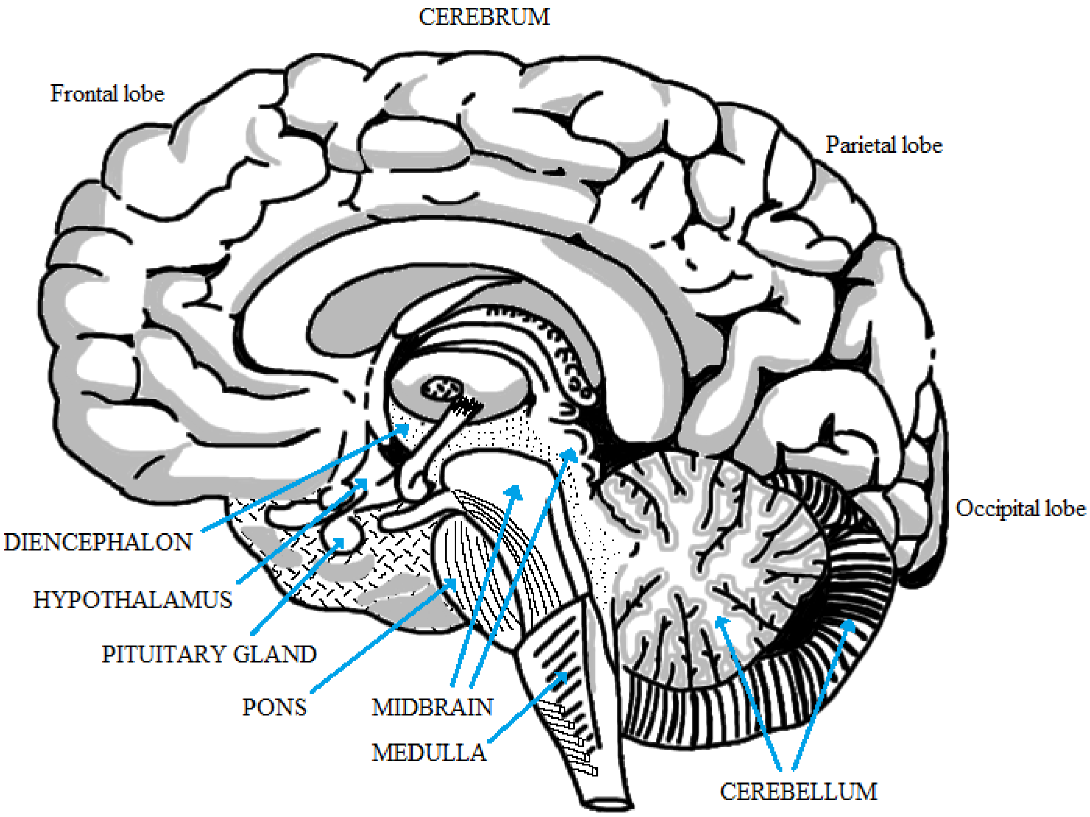

Figure 1. The anatomy of the brain. Pons, midbrain and medulla are all parts of the brain stem. Recreated from a figure by Malmivuo & Plonsey (1995) [19].

2.2. Electroencephalogram

The electroencephalogram (EEG) is a measurement of the activity of the cerebral cortex [4]. The human EEG goes all the way back to the year 1929 when

Austrian psychiatrist Hans Berger observed a distinctive difference between waking and sleeping EEGs. Even today, it is widely used to study sleep as well as to help in diagnosis of certain neurological conditions, most importantly the seizures of epilepsy. EEG measures small voltage fluctuations between selected pairs of electrodes on the scalp. These voltages are generated for the most part by electric currents in the pyramidal neurons of the cerebral cortex. Since a signal generated by a single cortical neuron is exceedingly small and it also must penetrate through several layers of non-neural tissue before reaching the electrodes, it takes a synchronous activation of thousands, even millions of neurons to generate a signal big enough to be detected by the electrodes [18]. EEG is indeed defined by the synchrony of the neurons, not by the total level of their activation. In fact, nonsynchronous activation of neurons often causes the signals to nullify one another because of opposing polarities.

EEG is usually recorded using an internationally standardized system called the 10-20 system, shown in Figure 2. [19]. In this system, 21 electrodes are located on different positions on the scalp using two reference points: nasion and inion. Nasion is the delve at the top of the nose that is in level with the eyes, while inion is the bony lump at the base of the skull on the midline at the back of the head. Using these reference points, the skull perimeters are measured in both transverse and median planes and electrode locations are then determined by dividing the perimeters into 10 % and 20 % intervals. While the 10-20 system is the international standard for EEG measurement, EEG can be measured using more or fewer electrodes than the 21 presented in the system.

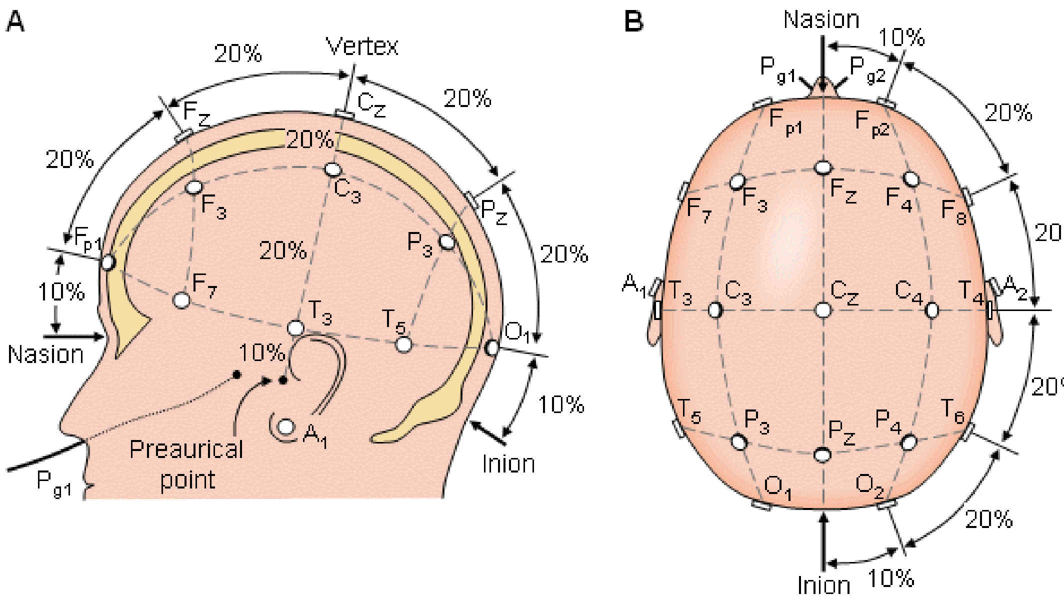

Figure 2. The 10-20 system seen from (A) left and (B) above the head. F = frontal, F_p = frontal polar, C = central, O = occipital, T = temporal, A = ear lobe, P_g = nasopharyngeal. Figure by Malmivuo & Plonsey (1995) [19].

Cortical neurons can oscillate in different frequencies, and certain frequency bands often correlate with states of behavior and pathology. Typically, these so-called brain waves are divided in delta, theta, alpha and beta waves, listed from lowest frequency range to highest. Frequency ranges are not standardized and therefore, there is a slight variation between them in literature. Delta waves (1-4 Hz) occur in very deep sleep, in infancy, and in serious brain pathologies such as coma [4], [18]. They often have voltages two to four times greater than most other brain waves. Theta waves (4-8 Hz) are common in the parietal and temporal regions in children. Although they are less prominent in adult EEG, they do occur sometimes during emotional stress, particularly during disappointment and frustration. Theta activity is also known to increase with cognitive load [20]. Pathology-wise, theta waves occur in many brain disorders, often in degenerative brain states [18].

Alpha waves (8-12 Hz) are the most dominant brain waves in the normal adult EEG [20]. They are especially prominent in wakeful participants that are asked to relax with eyes closed, and occur most intensely in the occipital region, although they can also be recorded from the parietal and frontal regions of the scalp. [18]. When eyes are opened and attention focused to some mental activity, alpha waves are replaced by beta waves (12-25 Hz). Increased activity of the brain leads to decreased synchronization of the signals, causing the brain waves to nullify one another. As a result, brain waves of lower voltage and higher frequency, beta waves, occur in the EEG. Examples of different brain waves are shown in Figure 3, as well as EEG spikes that can be seen during a petit mal seizure in epilepsy.

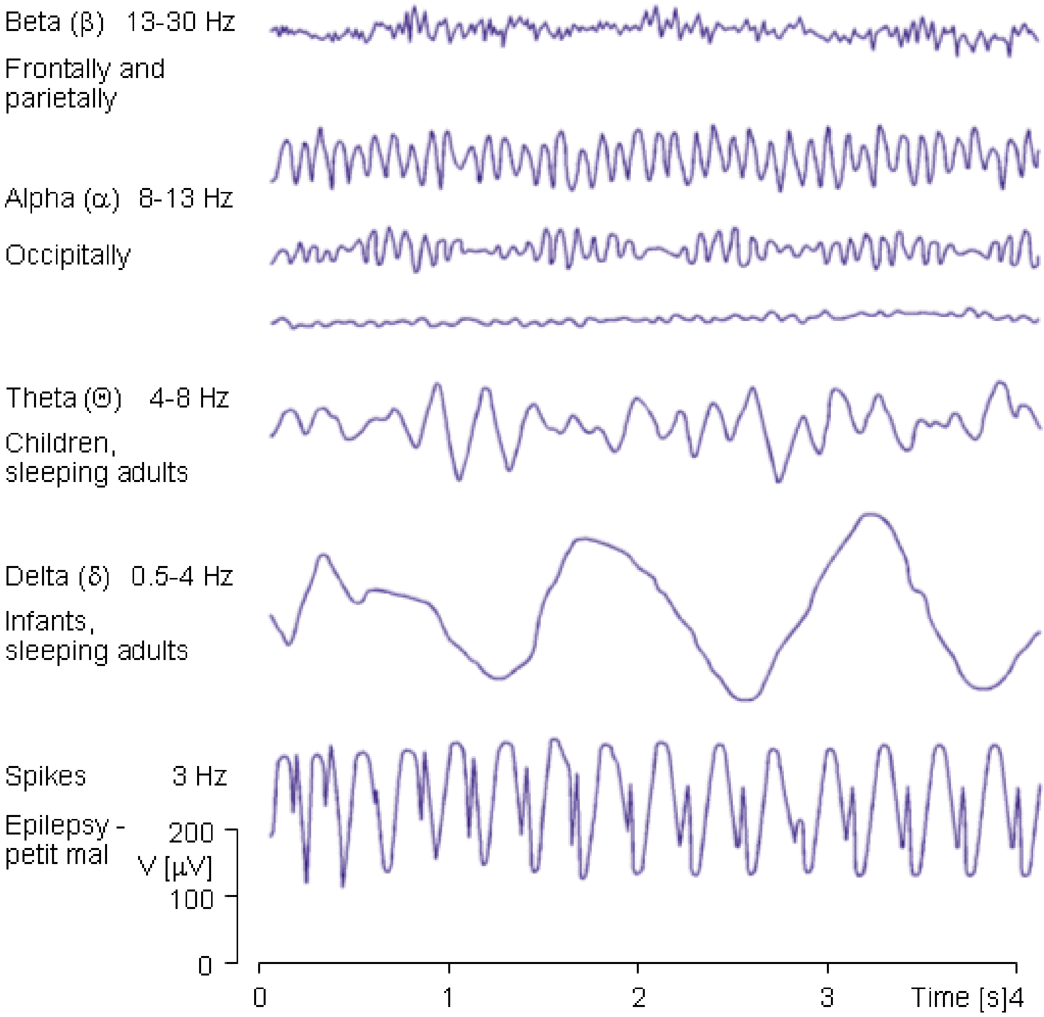

Figure 3. Examples of brain waves. Figure by Malmivuo & Plonsey (1995) [19].

2.3. Autonomic nervous system

The hypothalamus regulates the body through two pathways: hormonal secretion and neural control via the autonomic nervous system (ANS). The ANS is responsible for the control of most visceral functions of the body [18]. As the name suggests, these functions are mostly automatic and do not require conscious control as the ANS is mainly activated by centers located in the spinal cord, brain stem and hypothalamus. The ANS often operates through visceral reflexes meaning that it receives sensory signals from a visceral organ and returns subconscious reflex responses directly back to the organ to control its activities. There are two subdivisions in the ANS, the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS), that generally oppose each other. The SNS prepares the body for a crisis, real or perceived, while the PNS is more active during relaxation [4]. Common mnemonics for the two subdivisions are “fight-or-flight” for the SNS and “rest-or-digest” for the PNS. While one division is being active, the other tends to be quiet, as their general goals are incompatible.

The ANS and the somatic motor system form together the total neural output of the CNS [4]. The alpha motor neurons of the somatic motor system excite skeletal muscles with pinpoint accuracy and great speed. The ANS is very different as it can both excite and inhibit its peripheral targets in a more widespread area, and it is relatively slow compared to the somatic motor system. Both systems have upper motor neurons in the brain sending commands to lower motor neurons, but the systems are very different moving downward from the lower motor neurons. The cell body of a somatic lower motor neuron lies within the CNS, either in the ventral horn of the spinal cord or the brain stem. An ANS neuron also starts from the spinal cord or the brain stem but instead of going directly to the target tissue like a somatic motor neuron, it goes to a cell cluster called the autonomic ganglion where it synapses with another neuron. The neuron coming from the CNS to the ganglion is called the preganglionic neuron and the neuron proceeding from the ganglion to the target organ is called the postganglionic neuron. There are also anatomical differences between the SNS and the PNS. The preganglionic neuron of the SNS starts from the intermediolateral horn of the spinal cord and synapses in one of the ganglia of the sympathetic chain from where the postganglionic neuron continues to the target tissue or organ. As for the PNS, the preganglionic neuron starts either from the brain stem or from the lower (sacral) spinal cord and the ganglion where it synapses is typically located next to, on, or inside the target tissue or organ.

How do the two subdivisions of the ANS act when we are stressed out and conversely when we are relaxed? During stress, both physical and psychological, the SNS is active while the PNS stays quiet. Sympathetic stimulation increases the overall activity of the heart by increasing both the rate and force of contraction [18]. The increased propulsion of the heart together with the constriction of most blood vessels, i.e. increased resistance in blood flow, causes an acute increase in arterial blood pressure. The SNS also increases mental activity, activates sweat secretion from the sweat glands of the skin as well as increases the gas metabolism in lungs by the dilation of bronchi and mild constriction of blood vessels, among many other things. During relaxation, the SNS becomes quiet and the PNS takes control. This leads to opposite changes in the heart via the vagal nerves, that cause decrease in both the heart rate and force of contraction. Parasympathetic activation has virtually no effect on contraction of blood vessels, but arterial blood pressure is still slightly decreased due to a lesser blood flow. Mental activity goes back to normal, as does the sweating, and gas metabolism in lungs is decreased. Naturally, these are only a few examples of the effects of both the SNS and PNS.

2.3.1. Autonomic nervous system response

Since the ANS is so vast and versatile, there are many ways to measure which one of the subdivisions (SNS or PNS) is active. Heart rate (HR) is a simple yet very good ANS response. As mentioned earlier, HR is increased during sympathetic activation and vice versa, decreased during parasympathetic activation. Electrocardiography (ECG) is a traditional method for HR measurement: a 12-lead surface ECG is the current noninvasive gold standard for diagnosis of cardiovascular diseases such as myocardial ischemia or arrhythmia [21]. ECG measures electric activity of the heart, so not only can it be used for the calculation of HR, it also reveals possible abnormalities in the contraction of the heart. Photoplethysmography (PPG) is another method for HR measurement that has been on the rise for many years because of its convenience of use and low cost [10]. PPG is an optical, non-invasive bio-monitoring technique that measures blood volume changes in the microvascular tissue bed beneath the skin, resulting from the pulsatile nature of the circulatory system. From the variation of how much of the emitted light is absorbed and how much is reflected to the photo detector, many kinds of information can be acquired. Besides HR, PPG can measure oxygen saturation, respiration, heart rate variability and possibly even blood pressure. As PPG is measured from the periphery through skin, it is widely used in wearable devices, such as wristbands or a smart ring, like in case of this study.

Previously mentioned heart rate variability (HRV) is another great ANS response as it is able to index cardiac vagal tone, the contribution of the PNS to cardiac regulation [22]. A healthy heart is not at all static, but instead is constantly making adjustments to meet the needs of a situation. This means that generally, higher variability is a good thing, although some pathological conditions may cause an increase in HRV measurements [23]. HRV is the fluctuation in the time intervals between consecutive heartbeats called interbeat intervals (IBI). It can be measured through different time windows, described as 24 h, short-term (~5 min) and ultra-short-term (<5 min) HRV, and the types of the measurement can be divided in three categories: time-domain, frequency-domain and non-linear measurements. Time-domain measurements are quite straightforward, describing the amount of variability in measurements of the IBI either in original units or as the natural logarithm of original units. Frequency-domain measurements separate the IBI signal into four frequency bands, ultra-low, very low, low and high frequency, and calculate either the absolute or the relative power of the frequency band. Non-linear measurements can quantify for example the unpredictability of a time series, non-linearity meaning that the relationship between variables cannot be plotted as a straight line. Not only does HRV reflect regulation of autonomic balance, it can be used to estimate many other things, such as blood pressure, gas exchange, gut, heart and vascular tone.

During sympathetic activation, sweating is increased in the skin. When the sweat ducts are filled with sweat, that is both a weak electrolyte and good conductor, low-resistance parallel pathways are formed to the skin surface [5]. Changes in the skin conductance are referred as the electrodermal activity (EDA). EDA is a very promising tool for the measurement of the ANS responses, since it is solely determined by the activation of the SNS and it is measured from the skin surface, making it viable for usage in a wearable device. Finally, body temperature can also act as an indicator for the ANS. A stressful event causes core body temperature to increase, through the activation of the SNS [24]. This paradigm is called stress-induced hyperthermia. Conversely, peripheral temperature, measured from finger, has been shown to decrease during stress [25], [26]. Just like in EDA, the fact that peripheral temperature can be measured non-invasively from finger through skin means it can be used in wearable devices, such as smart rings.

2.4. Measuring stress

Stress is a part of our everyday lives and it serves a good purpose: stress prepares the body for an emotionally or physically challenging situation through activation of both HPA axis and the SNS. At best, stress is a force that pushes us forward and enables us to overcome the challenge. This type of stress, that is controlled and of limited duration, is called allostasis, meaning the process of maintaining the homeostasis by active means [1]. Allostasis is the so-called “good stress” and has protective effects on the body. When acute stress becomes chronic, however, it results to allostatic load or overload, a state where the stress hormones and other mediators are dysregulated. Allostatic load/overload has many forms, including prolonged response to a stressor, inadequate response to a stressor, or lack of adaptation to the same stressor. When stress is this type of “bad stress”, it can be very exhausting both physically and mentally, and it becomes a risk factor for many types of diseases, such as cardiovascular diseases, diabetes, cancer and depression [1], [3]. Chronic stress has also been noted to have enduring effects on the brain, and it has the highest impact on the structures that are either developing (in young individuals) or undergoing age-related changes (in adult and aged individuals) at the time of the stress exposure [27].

Because stress has such pervasive negative effects on human body, several studies have come up with ways to measure human stress level. Many of them have come up with different wearables, as they can enable a day-to-day stress measurement. EDA has been utilized in wearable devices because it directly reflects the activation of the SNS [5]. The problem with many EDA devices has been their large size and the placement of the electrodes being on fingers or palms, making the measurement quite uncomfortable. However, recently EDA has been measured from around wrist [5], [6], ankle [8] and from foot [9]. PPG is also a commonly used signal in wearables designed for stress measurement. HR and HRV, computed from a PPG signal, have been used in newly developed sensors [6], [8] as well as in validation of an already available commercial device, the Apple Watch [7]. Wearable sensors have also been used in development of an ambulatory stress monitor where electromyography (EMG) and respiration sensors were used in addition to a heart rate monitor and an EDA sensor [28].

In addition to the wearables measuring the ANS responses of the body, a commercially available EEG headband (Muse) has also been used for stress measurement [11]. EEG has also been used in a similar headband system that uses both EEG and HRV (computed from ECG) for continuous stress measurement [12]. Although a headband might not be as suitable for daily use as the previously mentioned wearables, it may give a more precise illustration of stress through reflection of the CNS. Combination of the CNS and ANS responses have been used for cognitive load measurement in a virtual reality -based driving system [13]. In the study, several physiological features (ECG, EMG, respiration, skin temperature, PPG, EDA) were used alongside with EEG, eye gaze features and driver performance in a system that through multimodal data fusion was able to measure cognitive load. Stress has also been measured during real-world driving tasks using ANS responses such as ECG, EMG, EDA and respiration as well as eye gaze [14], [15]. One of the more unorthodox ways to measure stress has been via thermal imaging [16]. The method used in the study was able to capture stress induced neurophysiological responses on the perinasal area that manifest as transient perspiration.

2.5. Objectives

In this study, outputs from the CNS and ANS were measured in a mentally stressful situation versus a relaxing situation, using a polysomnography system for the CNS and a smart ring for the ANS measurement. The objective was to compare the outputs in both phases and to find correlations between the two measurements, in order to evaluate the possible usage of a smart ring for indirect measurement of human stress level.

3. METHODS

3.1. Setup

Two measurement devices were used in the study: Nox A1 PSG System by Nox Medical and Oura ring (2018 model) by Oura Health, Oulu, Finland. The Nox A1 is a fully portable polysomnography system that has inputs for electroencephalography (EEG), electrooculography (EOG), electromyography (EMG), electrocardiography (ECG) and respiratory inductive plethysmography (RIP) [29]. It can also measure subject's airflow using either a nasal cannula or a mask and it has a microphone for recording of respiratory sounds. Oura ring includes a body temperature sensor, infrared LEDs and photodetectors that measure blood volume pulse directly from the palmar arteries of the finger, and 3D accelerometers and gyroscope that detect the amplitude and intensity of body movement [30].

All the electrode positioning and channel decisions in Nox A1 were made following the AASM Manual for the Scoring of Sleep and Associated Events [31]. In this study, all the inputs were used apart from airflow and two leg EMGs. Nox A1 measures EEG using nine electrodes: F4 & F3 electrodes in the frontal, C4 & C3 electrodes in the central and O2 & O1 electrodes in the occipital area of the scalp. M2 & M1 mastoideus electrodes were used as reference and center of forehead as ground. E2 & E1 electrodes were placed next to both eyes for combined vertical and horizontal EOG measurement. Three EMG electrodes were placed on the chin so that the ground electrode was in the middle and the other electrodes were on left and right sides of the chin. Two ECG electrodes were placed on opposite sides of the heart so that one electrode was on the left side on the ribs and the other was on the right side below the collarbone, producing the ECG Lead II. RIP was measured using two belts, of which one was placed around the thorax and the other around the abdomen. Total of four Oura rings were used and they were placed around the index and the ring fingers in both hands. Nox A1, Oura rings and the electrode layout can be seen in Figure 4.

Figure 4. Electrode layout, Nox A1 and Oura ring.

3.2. Measurements

There were ten test subjects in the study, five male and five female, aged 23-26. On the test day, subject needed to be healthy, free of any medication that could affect their mental state and they had not drunk coffee, energy drinks or other stimulants for the last four hours. Test subject could not suffer from depression, anxiety or other mental illnesses. They also needed to be regular weight (body mass index in the range of 18.5 – 24.9 kg/m2) [32] and could not suffer from cardiovascular diseases. Before the measurement, subject filled a form containing basic information (age, gender, height, weight) and signed a form of consent.

The measurement consisted of a protocol that was designed to either make the subject relax or cause them stress. In the current study, data from two specific phases of the protocol, representing best the relaxation and mental stress, were used. These phases were a meditation phase and a mental calculation phase. Additionally, a third phase was chosen as a baseline. In all phases, subject was sitting still with their eyes closed to minimize the artefacts caused by muscles or eye movement. Meditation phase was ten minutes in duration while baseline and mental calculation phases were both five minutes. Subject was informed beforehand about the meditation and stress phases, but the details were not revealed until at the start of the phases. Average placement of considered phases in the measurement protocol is viewed in Figure 5.

For the meditation phase, an iPhone application called Oak was used. A ten-minute meditation program was chosen with female voice instructions and a sound of a stream in the background, played through a Bluetooth speaker. Ambient sounds were blocked by conducting experiments in a soundproofed room. The room was also air-conditioned, and the ambient temperature was maintained constant in approximately 21 °C. The meditation was a focused attention exercise, where the subject was instructed to focus only on breathing and let all the excessive thoughts behind.

In the mental calculation phase, subject's task was to start from the number 2485 and subtract number seven continuously from the previous number. After each calculation, the subject had to say aloud the next number and they were corrected if they made a mistake. This continued for two minutes, after which the task started changing. The subject had to either add or subtract a number that was told to them and the number changed on average after three calculations. The purpose of this was that the subject wouldn't get used to counting with one number only.

Finally, during the baseline phase subject was simply told to relax and let their thoughts wander freely, with no need to focus on anything.

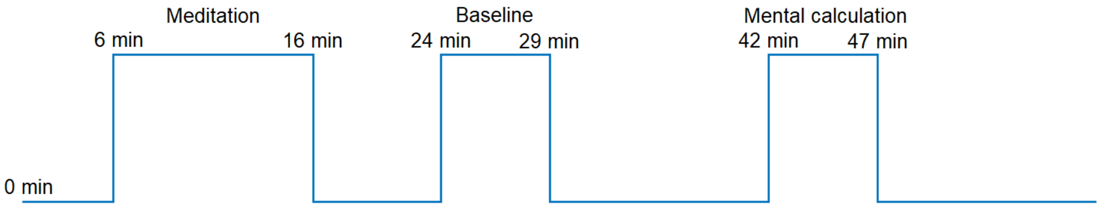

Figure 5. Average placement of considered phases in the measurement protocol.

3.3. Analysis

Analysis was performed using MATLAB R2019a. As mentioned earlier, all the data for this study came from Nox A1 and the Oura rings. Since the rings were all slightly in different time, first task was to synchronize their time with Nox's time. The Oura ring records interbeat intervals (IBI) while Nox records ECG. An IBI signal was calculated from the Nox ECG using peak detection. After this, Nox IBIs and ring IBIs were plotted, and time differences observed from the figures. Analyses were performed for each subject separately since the number of subjects (N = 10) was small.

Two types of data were used from the ring data: IBI and temperature data. IBI was used to calculate mean HR and root mean square of the successive R-R differences (RMSSD) for both phases of the measurement, RMSSD being a time-domain index of HRV. Temperature data was used to calculate peripheral temperature changes in both phases. The ring parameters have been validated in previous studies. A comparison of HR and RMSSD between the Oura ring and an ECG device showed a high correlation for both HR ($r2 = 0.998$, $p < 0.001$) and RMSSD ($r2 = 0.967$, $p < 0.001$) [33].

Since the ring features reflect the responses of the ANS, processing of Nox data focused on EEG to get the corresponding responses from the CNS. EEG and EOG channels were filtered with lowpass, notch and highpass filters to eliminate white noise, power line interference and baseline wandering. Furthermore, EMG signal from the chin area was used in the analysis after running it through a highpass filter. Examination of EEG revealed that the signal looked very different in the mental calculation phase. There did not seem to be artefacts from the EOG, for the subject's eyes were closed the whole time. However, during the mental calculation phase, subject was instructed to say the numbers aloud, which caused muscular activity that could be seen in the EMG. To ensure that the frequencies in the EEG were from the brain itself and not from nearby muscles, processing of EMG was necessary.

The idea was to pick up the points in EMG, where the muscle activity was higher, and remove the corresponding points from the EEG. To get the EMG in a more suitable form, it was first rectified and then filtered with a moving average filter. Now it was possible to choose a threshold: if the EMG amplitude passed the threshold, the points were removed from the EEG. Since the impedances of EMG electrodes varied between the subjects, the threshold was chosen for all the subjects separately. After the invalid points were eliminated, power spectral densities (PSD) of two frequency bands, alpha (8-12 Hz) and beta (12-25 Hz), were calculated for all the continuous segments in mental calculation and meditation phases. Only the alpha and beta frequency bands were chosen, since delta is mainly seen in deep sleep state and theta is also less prominent in normal EEG [18], [20]. If the segment was too short for the alpha and beta channels, it was simply ignored. Finally, after the PSDs for all the segments were calculated, mean values for both alpha and beta bands were calculated.

Figure 6 shows the analysis steps with a detailed description of the signal processing. Bandpass (consisting of lowpass and highpass filters) and notch filtering are common in EEG processing [34]. Notch filtering has been criticized before because it can produce a high-frequency ringing artifact to the signal, which can then be mistaken for fast oscillatory brain activity [35]. However, in this study signal was processed offline and hence, notch filter could be applied using zero-phase digital filtering, avoiding any phase distortion. As for EMG, highpass filtering is required when performing a rectification before averaging the signal [36]. As mentioned earlier, purpose for using rectification and averaging was to get the signal in a more suitable form. After the filtering, it was effortless to detect the points where EMG was active, i.e. the subject was talking, and remove the corresponding points from EEG.

In the Nox data analysis, EEG of two subjects were left unused due to disturbances in the measurement. Additionally, one subject was missing temperature data and therefore peripheral temperature changes could not be computed for the subject. HR and HRV (RMSSD) were successfully retrieved from all the subjects. Finally, an analysis of variance (ANOVA) was performed for each parameter using Matlab's one-way ANOVA function `anova1`. A probability value (p-value) greater than 0.05 supports null hypothesis and a p-value smaller than 0.05 suggests statistical significance.

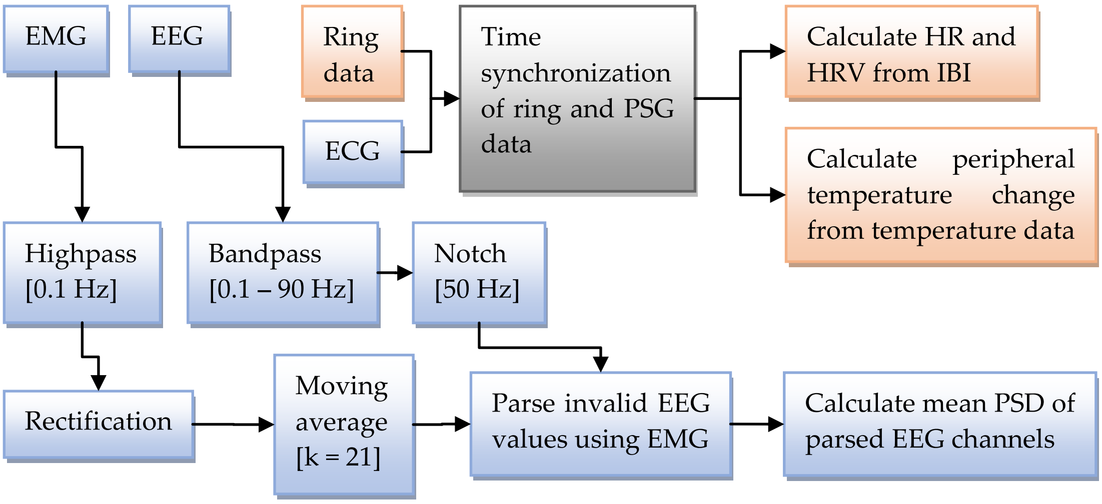

Figure 6. Analysis steps where blue boxes indicate Nox data analysis and orange boxes indicate ring data analysis. Bandpass consisted of two finite impulse response (FIR) filters: lowpass with a Hamming window and a least-squares highpass. Notch filter was an infinite impulse response (IIR) filter that was applied using Matlab's `filtfilt` function (zero-phase digital filtering) to avoid phase distortion. EMG rectification was done by subtracting the mean EMG from the signal after which absolute values of the signal were taken. Moving average filter was applied using Matlab's `movmean` function with a window length of 21 samples.

4. RESULTS

In results, the mental calculation phase is referred to as cognitive stress while the meditation phase is referred to as relaxation. Table 1 and 2 present relaxation and cognitive stress values, respectively, for all the parameters. For EEG PSD, HR and HRV (RMSSD), absolute values of relaxation and cognitive stress were divided by the corresponding baseline value to eliminate the different offsets between the subjects. Meanwhile, peripheral temperature change has its values in degrees of Celsius.

Table 1. Relaxation values of EEG PSD, HR, HRV (RMSSD) and peripheral temperature change. EEG PSD, HR and HRV (RMSSD) values are relative to the baseline value.

ID	**Alpha (EEG PSD)**	**Beta (EEG PSD)**	**HR**	**HRV (RMSSD)**	**Perip. temp. change [°C]**
1	-	-	1.009	1.054	0.2400
2	1.210	0.9476	1.033	1.034	-0.1500
3	0.9093	0.8464	0.9839	1.295	1.465
4	0.7268	1.232	1.079	0.9418	0.4900
5	0.8011	0.8003	1.056	0.7907	0.0200
6	0.6990	0.8673	1.132	0.9361	1.240
7	1.096	1.036	1.074	0.9504	-
8	1.045	0.4617	0.9888	1.045	1.230
9	-	-	1.017	1.496	0.1800
10	1.253	2.544	1.022	1.060	0.3600
Median	0.9773	0.9075	1.028	1.040	0.3600
Range	0.6990 – 1.253	0.4617 – 2.544	0.9839 – 1.132	0.7907 – 1.496	-0.1500 – 1.465

Table 2. Cognitive stress values of EEG PSD, HR, HRV (RMSSD) and peripheral temperature change. EEG PSD, HR and HRV (RMSSD) values are relative to the baseline value.

ID	**Alpha (EEG PSD)**	**Beta (EEG PSD)**	**HR**	**HRV (RMSSD)**	**Perip. temp. change [°C]**
1	-	-	1.471	0.5131	0.3100
2	0.5008	1.571	1.074	1.146	-0.5500
3	0.7973	0.9179	1.183	1.187	-0.5150
4	0.8687	3.262	1.539	0.2504	0.0100
5	2.127	1.657	1.110	0.7176	-0.4100
6	2.478	2.565	1.270	0.8776	-0.2100
7	2.340	1.877	1.490	0.5350	-
8	0.5953	1.192	1.113	0.8286	-3.910
9	-	-	1.165	1.392	-0.6200
10	2.594	3.453	1.442	0.4219	0.0900
Median	1.498	1.767	1.226	0.7731	-0.4100
Range	0.5008 – 2.594	0.9179 – 3.453	1.074 – 1.539	0.2504 – 1.392	-3.910 – 0.3100

Changes in values between relaxation and cognitive stress are visualized in Figures 7 and 8. In Figure 7, the EEG PSD, HR and HRV (RMSSD) values of the cognitive stress were divided by the values of relaxation phase to get a clear comparison between the two phases. For peripheral temperature change similar scaling was not profitable. Figure 8 shows the transitions of values for all the subjects, where the measured values are presented as circles and each line represents one subject. Similarly to the Tables 1 and 2, all but peripheral temperature change have their absolute values divided by the corresponding baseline value.

Considering the medians of cognitive stress and relaxation phases, in cognitive stress the EEG alpha and beta powers increased by 53.26 % and 94.70 %, respectively, compared to values observed in the relaxation phase. HR also increased by 19.33 %, while HRV (RMSSD) decreased by 25.65 % and peripheral temperature change was 0.77 ℃ lower. Results of ANOVA presented in Table 3 show that the increase of alpha power is not statistically significant with p-value greater than 0.05. Also, HRV (RMSSD) has a p-value slightly greater than 0.05. However, beta power, HR and peripheral temperature change have p-values smaller than 0.05, indicating that their changes are statistically significant.

Table 3. ANOVA of EEG PSD, HR, HRV (RMSSD) and peripheral temperature change. SS = sum of squares, DF = degrees of freedom, MS = mean squared error, F = F-statistic (ratio of MS), P = p-value

Parameter	**Source**	**SS**	**DF**	**MS**	**F**	**P**
Alpha (EEG PSD)	Between Groups	1.300	1	1.300	2.900	0.1106
	Within Groups	6.274	14	0.4482		
	Total	7.574	15			
Beta (EEG PSD)	Between Groups	3.763	1	3.763	5.930	0.0288
	Within Groups	8.877	14	0.6341		
	Total	12.64	15			
HR	Between Groups	0.3029	1	0.3029	17.33	0.0006
	Within Groups	0.3146	18	0.0175		
	Total	0.6175	19			
HRV (RMSSD)	Between Groups	0.3739	1	0.3739	4.230	0.0544
	Within Groups	1.589	18	0.0883		
	Total	1.963	19			
Peripheral temperature change	Between Groups	6.576	1	6.576	6.730	0.0196
	Within Groups	15.63	16	0.9769		
	Total	22.21	17			

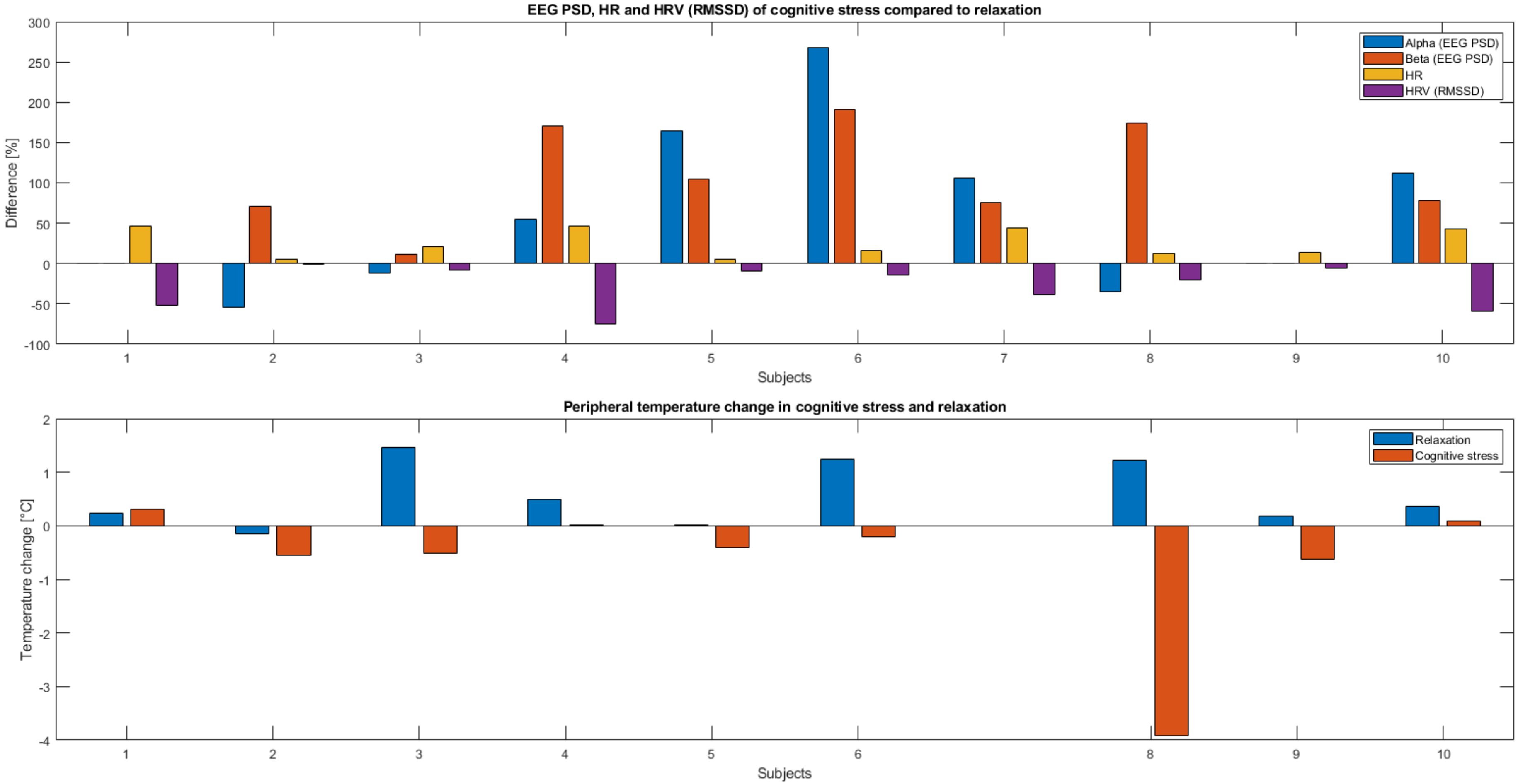

Figure 7. Relative differences of EEG PSD, HR and HRV (RMSSD), and absolute changes of peripheral temperature. EEG PSDs for subjects 1 and 9 as well as peripheral temperature changes for subject 7 could not be calculated.

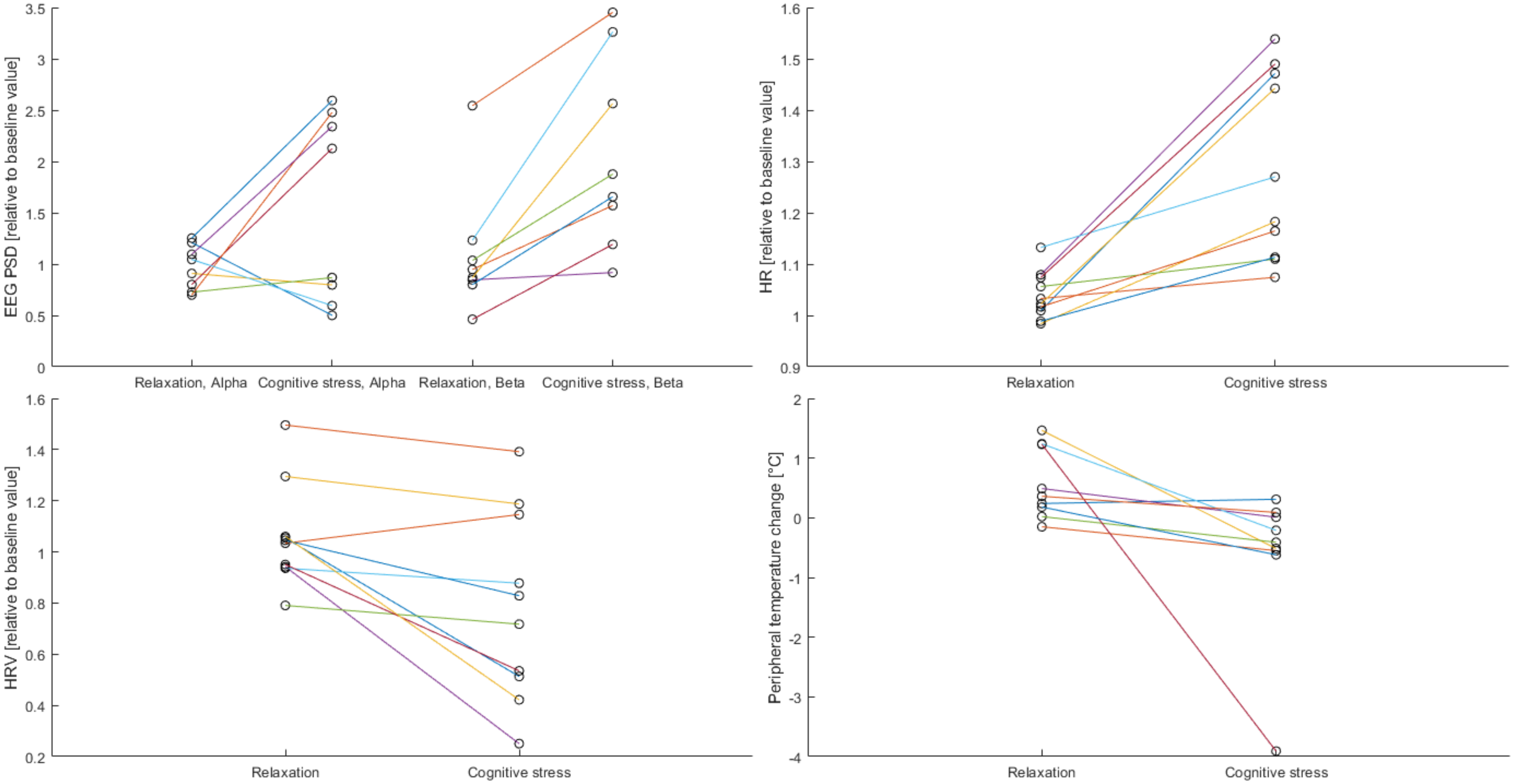

Figure 8. Transitions of EEG PSD, HR, HRV (RMSSD) and peripheral temperature change values for different test subjects. One line equals one subject.

5. DISCUSSION

Changes in the CNS responses presented by EEG PSD indicate that the subjects were indeed experiencing cognitive stress during the mental calculation task while being more relaxed in the meditation phase. Corresponding changes in the ring features, reflecting the responses of the ANS, correlate with this finding. This suggests that a smart ring such as Oura could be used for an indirect measurement of the human stress level.

To be able to detect cognitive stress, a smart ring should differentiate stress caused by physical activity from the one caused by cognitive load, since they both appear quite similarly in the ANS response. For this, accelerometer data could prove useful. When the stress markers, such as high HR and low HRV, are visible but the person is staying relatively still, stress is more likely to be mental. On the other hand, there are physical activities that do not require movement but are instead static, e.g. planking, which means accelerometer alone is not enough for the separation. Of the previously considered ring features, peripheral temperature acts differently whether the stress is physical or mental. During physical activity, blood flow to the skin increases, transferring heat from the core of the body to the surface and therefore increasing the peripheral temperature [18] while in cognitive stress peripheral temperature has been noticed to decrease [25], [26].

Examining the changes of values in all the features, in EEG PSD beta power was higher during cognitive stress compared to relaxation for all the subjects. Alpha power also increased in most of the cases, excluding subjects 3 and 8. HR values increased and HRV values decreased for all the subjects when moving from relaxation to cognitive stress. Finally, peripheral temperature changes in cognitive stress were negative in all cases except for subjects 1 and 10, while in relaxation they were positive except for subject 2. However, when comparing cognitive stress to relaxation, the value of the temperature change was smaller during cognitive stress in all cases.

The increase in beta power in the cognitive stress phase was expected, since beta activity is associated with intense mental activity [18]. However, the increase in alpha power in cognitive stress compared to relaxation is rather interesting, because alpha waves have been linked to a more relaxed state of the brain. On the contrary, increased attention, alertness and task load in general have been linked to decrease in alpha power [37]. That being said, alpha waves have also been noted to have different properties: alpha oscillations have been said to indicate that “attention is actively suppressing cortical activity related to distractors as a part of the process of focusing attention on important targets”. This could indicate that the increase in alpha power could be related to the brain’s need to suppress the competing information sources during the mental calculation task. Regardless, examining the p-values of both alpha and beta, only the increase in beta power seems to be statistically significant, suggesting that the increase in alpha might not matter so much.

Higher HR and lower HRV in the cognitive stress both advocate for activation of the SNS. When HR is higher, the time between successive beats is narrowed, which in turn means that the opportunity for the IBIs to vary is also reduced [23]. When IBIs are varying less, HRV is lower. Vice versa, in relaxation when HR was lower, the time between successive beats was wider giving the IBIs higher chances to vary and thus raising the HRV. This phenomenon is called cycle length dependence.

Moreover, the peripheral temperature changes being mostly negative in cognitive stress is in line with previous findings, where peripheral temperature has been noticed to decrease during stress exposure [25], [26]. HRV (RMSSD) is the only ring feature that has a p-value greater than 0.05. However, this would most likely be fixed if the group was larger.

In the mental calculation phase the EMG was leaking to EEG and the “corrupted” parts were removed from the EEG. This unfortunately led to losing of data. It is also not completely certain that the remaining EEG would originate solely from the brain even after the processing. The EEG analysis could be improved by implementing e.g. independent component analysis (ICA) or other methods that could reliably separate the EEG and EMG signals. The ring data also suffered from data loss: some rings, for unknown reason, failed to record data during the measurement. Generally, this was not a problem since there were four rings for one subject. However, for the subject 7 the data loss was significant, since only one ring was able to record IBI and none were able to record temperature data. Finally, the number of subjects was small and limited including only healthy young adults. To achieve a more statistically significant result, a follow-up study with larger group is needed with people from different age groups and with different conditions.

All in all, despite of the mentioned downsides, this study was successful, especially for the ring data analysis part where no problems were encountered. The mental calculation phase was enough to cause cognitive stress to the test subjects, with the increase in HR being the most visible change. Objectives of this study were well met. Still, further studies are needed to explore the physiological changes in stress compared to relaxation and to determine the most suitable features to represent stress. The ultimate goal would be to measure the stress level on a daily basis, e.g. using the Oura ring similar to this study. This way the person could monitor their stress and make necessary changes in order to achieve a healthier, less stressful lifestyle.

6. CONCLUSION

This study focused on measuring the responses of central and autonomic nervous systems, using a polysomnography system (Nox A1) and a smart ring (Oura), in two conditions: cognitive stress induced by a mental calculation task and relaxation induced by a focused attention meditation exercise. EEG showed higher alpha and beta activity in cognitive stress compared to relaxation. Additionally, HR increased while HRV (RMSSD) and peripheral temperature decreased. The ANS responses measured using Oura ring were in line with the CNS responses measured using Nox A1, indicating that the indirect measurement of the stress level could be possible using a smart ring such as Oura. Follow-up studies with larger sample sizes are needed to confirm the findings of this study and to determine the most suitable features for representation of human stress level.

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