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Cardiovascular Parameters During Mental and Physical Stress in Hypertensive Patients

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Kurzfassung

Stress ist eine der Hauptursachen für eine Reihe von schweren Krankheiten. Es gibt mehrere invasive und nicht-invasive Methoden, um Stress zu quantifizieren und zu überwachen. Die Auswirkungen von psychischem oder physischem Stress auf kardiovaskuläre Parameter in einer gesunden Gruppe standen bereits oft im Mittelpunkt vieler Studien. Um die Auswirkungen von psychischem oder physischem Stress auf eine hypertensive Gruppe zu untersuchen, wurden in dieser Studie verschiedene kardiovaskuläre Parameter von 48 TeilnehmerInnen mit erhöhtem Blutdruck oder Hypertonie überwacht.

Die TeilnehmerInnen der Studie wurden in drei verschiedene Zustände versetzt, einen Ausgangszustand, der zu Beginn wiederholt wurde, einen Stresszustand, der entweder ein Demtect-Test oder Treppensteigen war, und einen Erholungszustand nach der Stresssituation. Mit einem mobilen Gerät wurden Elektrokardiogramm- und Puls-Photoplethysmogramm-Daten kontinuierlich aufgezeichnet, und auf Grundlage der Signale wurden Pulsankunftszeiten *PAT*, Herzraten *HR*, Herzratenvariabilität (HRV)-Daten und Pulswellencharakteristika berechnet und ausgewertet. Kardiovaskuläre Parameter zwischen den verschiedenen Gruppen von Belastungsmodi und Blutdruckklassen sowie Alter und Geschlecht wurden statistisch ausgewertet, sowie Differenzen Δ zwischen Beginn und Ende der Messung.

Während beiden Aufgaben nahm die Aktivität des Sympathikus zu und die des Parasympathikus ab, indem Blutdruck, *HR* (ΔHR mental 4.45 1/min, physisch 35.21 1/min) und das Verhältnis von Niederfrequenz- zu Hochfrequenzleistung *LF/HF* ($\Delta LF/HF$ mental 1.13, physisch 1.29) stiegen, und Inflectionpoint-Fläche *IPA* (ΔIPA mental -0.18, physisch -0.46) sanken. Die Veränderungen der Parameter waren bei der mentalen und der körperlichen Aufgabe unterschiedlich ausgeprägt, sodass die körperliche Aufgabe stärkere Reaktionen und Veränderungen auslöste. Trotz eines Anstiegs des systolischen Blutdrucks *SBP* und der *HR* während der mentalen Aufgabe fiel *PAT* (ΔPAT mental -9.31 ms, physisch -58.13 ms) kaum ab. Die Standardabweichung der Artefakt bereinigten RR-Intervalle *SDNN* ($\Delta SDNN$ mental 8.26 ms, physisch 3.05 ms) stieg an, *RMSSD* blieb unverändert, was darauf hindeutet, dass die mentale Aufgabe leichtere HRV-Reaktionen hervorrief. In der Erholungsphase nahm jedoch die Parasympathikus-Aktivität zu und die Sympathikus-Aktivität blieb bei der mentalen Aufgabe gleich, während bei der körperlichen Aufgabe der gegenteilige Fall auftrat, denn hier blieb die Parasympathikus-Aktivität gleich und die Sympathikus-Aktivität nahm ab.
Bei HypertonikerInnen und ProbandInnen mit erhöhtem Blutdruck stieg während beider Aufgaben *LF/HF*s ($\Delta LF/HF$ 1.40) an, jedoch auch *SDNN* ($\Delta SDNN$ 10.75 ms). TeilnehmerInnen mit erhöhtem Blutdruck und Hypertonie zeigten jedoch keine Erholung nach der Aufgabe mit einem erhöhten *RMSSD*-Wert, während dies bei normotensiven Personen der Fall war ($\Delta RMSSD$ 7.31 ms). Darüber hinaus wiesen HypertonikerInnen einen allgemein

erhöhten arteriellen Gefäßtonus auf, da die *PAT*-Werte in den Ruhezuständen am niedrigsten waren und sich die *IPA*-Werte nach der Aufgabe nicht erholt hatten.
Die Korrelationen zwischen *SBP* und *PAT* waren signifikant, aber nicht ausreichend. Die Korrelationskoeffizienten variieren zwischen -0.30 bis 0.32, aber Korrelation zwischen *HR* und *PAT* in der Erhohlungsphase zeigte mit einem Korrelationskoeffizienten von -0.61 eine Synchronisation.

Die Daten zeigten, dass der Zusammenhang zwischen *PAT* beziehungsweise der zugrundeliegenden Pulswellengeschwindigkeit und dem Blutdruck nicht trivial ist, sondern mit dem Geschlecht, dem Alter und den kardiovaskulären Risikofaktoren zusammenhängt. Außerdem reagieren die Herz-Kreislauf-Parameter von HypertonikerInnen nicht mehr auf alle Stresssituationen. Eine explizit längere Erholungszeit nach einer körperlichen oder geistigen Anstrengung kann weder bei HypertonikerInnen noch bei normotensiven TeilnehmerInnen festgestellt werden.

Diese Arbeit präsentiert eine Studie um etwaige Unterschiede zwischen einem mentalen und physischen Stress bei hypertensiven und normotensiven TeilnehmerInnen festzustellen. Die erzielten Ergebnisse zeigen keine erhöhte Reaktivität auf mentalen Stress, weder bei normotensiven noch bei hypertensiven TeilnehmerInnen. Eine eindeutig verschlechterte Erholung kann ebenfalls bei keiner der Gruppen festgestellt werden. Studien unter Berücksichtigung anderer Stressreize wären für die Bestätigung der Ergebnisse hilfreich.

Abstract

Stress is a major burden for the society and is one of the leading causes for a number of serious diseases. There exist several invasive and non-invasive methods to quantify the stress and to monitor it. However, mostly the effects of mental or physical stress on cardiovascular parameters in a healthy population have been the focus of many studies. In order to investigate the effects of mental or physical stress on a hypertensive population, various cardiovascular parameters of 48 hypertensive participants with elevated blood pressure or hypertension were monitored in this study.

Participants of the study were placed in three different states, a baseline state that occurred twice at the beginning, a stress state that consisted of either a Demtect test or climbing stairs, and a recovery state after the stressful situation. With a hand-held device, electrocardiogram and pulse-photoplethysmogram data were continuously recorded and based on those signals pulse arrival time *PAT*, heart rate *HR*, heart rate variability (HRV) data and pulse wave characteristics were calculated and evaluated. Cardiovascular parameters between the different groups of stress modes and blood pressure classes as well as age and sex were statistically evaluated, as well as differences Δ between the beginning and end of the measurement.

During both tasks, sympathetic nervous system (SNS) activity increased and parasympathetic nervous system (PNS) activity decreased, resulting in an increase in blood pressure, *HR* (ΔHR mental 4.45 1/min, physical 35.21 1/min) and ratio of low frequency to high frequency power *LF/HF* ($\Delta LF/HF$ mental 1.13, physical 1.29), and resulting in a decrease in inflection point area *IPA* (ΔIPA mental -0.18, physical -0.46). The changes in parameters were different for the mental and physical tasks, such that the physical task elicited stronger responses than the mental one. Despite an increase in systolic blood pressure *SBP* and *HR* during the mental task, *PAT* barely fell (ΔPAT mental -9.31 ms, physical -58.13 ms). The standard deviation of normal-to-normal intervals *SDNN* ($\Delta SDNN$ mental 8.26 ms, physical 3.05 ms) increased and the root mean square of successive RR differences *RMSSD* remained unchanged, indicating that the mental task elicited lighter HRV responses. After the mental task, PNS activity increased and SNS activity remained the same, whereas after the physical task the opposite was observed, here PNS activity remained the same and SNS activity decreased.
Hypertensives and subjects with elevated blood pressure showed an increase in *LF/HF*s ($\Delta LF/HF$ 1.40) during both tasks, but also an increase in *SDNN* ($\Delta SDNN$ 10.75 ms). They showed no recovery after the task with an increased *RMSSD* value, whereas normotensive subjects did ($\Delta RMSSD$ 7.31 ms). In addition, hypertensives had generally increased arterial vascular tone, as *PAT* values were lowest at rest and IPA values did not recover after the task.

The correlations between SBP and PAT were significant but not sufficient. The correlation coefficients varied from -0.30 to 0.32, but correlations between HR and PAT in the different phases showed synchronisation in the recovery phase with a correlation coefficient of -0.61.

The data showed that the relationship between PAT or the underlying pulse wave velocity with blood pressure is not quite so trivial, but it depends on age, sex and cardiovascular-risk factors. Moreover, cardiovascular parameters of hypertensives no longer respond to all stressful situations. An explizitly longer recovery after the mental or physical task in the hypertensive or normotensive participants cannot be stated.

This paper presents a study to determine any differences between mental and physical stress in hypertensive and normotensive participants. The results obtained show no increased reactivity to mental stress, neither in normotensive nor in hypertensive participants. A clearly deteriorated recovery can also not be determined in any of the groups. Studies taking into account other stress stimuli would be helpful to confirm these results.

Acknowledgement

First of all, my gratitude belongs to Dipl.-Ing. Dr. Martin Bachler, who made this thesis possible and who supervised and examined my Master thesis. I would like to express my sincere thanks for all the suggestions, assistance and constructive criticism in this thesis. Special thanks go to all the participants of the study, without them, this study would not be possible.

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Contents

1 Introduction

Hypertension is termed the "silent killer", because there are almost no symptoms and warning sings, and thus the majority of people are unaware of the problem [1]. Since hypertension is also an important risk factor for almost all cardiovascular diseases [2], which is still the leading cause of death wordwild [3], high blood pressure needs to be detected and treated. To properly detect hypertension and thus prevent its clinical outcome, blood pressure needs to be measured routinely [1]. There are different ways to measure blood pressure, but until recently, a non-invasive, non-obstructive and continuous method was not possible.
The gold standard of continuous blood pressure measurements is by means of a catheter inserted in an artery. It provides continuous and accurate data but due to its invasive nature, it is usually reserved for intensive care units. From the non-invasive side, the auscultatory measurement is the standard approach, which is based on the Korotkoff sounds [4, 5]. However, continuous data cannot be recorded and a medical supervision is required. Oscillometric methods, volume clamp and tonometry methods are either associated with an inflatable cuff, which may cause discomfort to the patient, or they need to be calibrated [6]. The pulse arrival time gained popularity to monitor blood pressure data and changes, due to the simplicity of electrocardiogram and photoplethysmogram aquisition [7]. Owing to the technological advances in the fields of wearable sensors, minitaruization and wireless data collection, the recording of pulse arrival time and pulse wave features to monitor blood pressure changes is now becoming much easier and more convenient for the patient [4, 5].
Mental or physical stress is an inevitable part of daily life to which the body reacts with increases in heart rate, blood pressure, cardiac output [8] and reduced heart rate variability [9] and thus influences the pulse arrival time data as well. Exaggerated responses to stressful situations, chronic stress but also acute stress can favour the development of cardiovascular diseases, such as artherosclerosis, hypertension or myocardial infarction [10, 11, 12]. The observed cardiovascular responses to mental or physical stress are mostly based on a healthy sample population and not on people with elevated hypertension or other cardiovascular diseases.
The different patterns of response to stress in a hypertensive population could give rise to further research on the relationship between stress and cardiovascular diseases, as well as insights into the relationship between blood pressure and pulse arrival time or the pulse wave velocity.

1.1 Objective

For this reason, the aim of this thesis is the analysis and evaluation of electrography, photoplethysmography and blood pressure signals in hypertensive patients during stressful situations. Data of the thesis belong to a medical study conducted at the center for interdisciplinary medicine, diagnostic and therapy in Dortmund, Germany in cooperation with the Austrian Institue of Technology in Vienna. These measurements took place at rest, during physical or mental stress and after the stress. Since the body not only reacts to stress with changes in one cardiovascular parameter, but the entire cardiovascular and neuro-endocrine system is affected, several cardiovascular parameters are considered. Pulse arrival time, heart rate, heart rate variability and pulse contour parameters are used for this pupose. These parameters are to be adjusted on the basis of signal quality and assigned to the appropriate groups. Using proper statistical methods, these aggregated data will be presented, related to each other and analysed using the computing environment MATLAB®2021a. Finally, the results will be compared with those from literature and discussed.

1.2 Structure

This thesis is organised in four major parts. At the beginning, the most important physiological and technical principles are presented, including the cardiovascular system, the pathology of hypertension, the pulse wave with corresponding pulse arrival time, the concept of stress, and its effects on the body. A brief description of the different blood pressure measurement methods and their advantages and disadvantages is also given.
The second part of the thesis describes the underlying medical study with a newly developed device with which the data was recorded. Besides, it is also stated how the data is analysed and how statistical evaluation is performed.
The evaluation of the data and the visual presentation is discussed in the next chapter, followed by the comparison of the results with literature and their discussion. At the end, the thesis is recapitulated and prospects for further work are proposed.

2 Background

For a better understanding of the pulse arrival time and the other cardiovascular parameters, a comprehensive physiological understanding is essential. Therefore, the next chapters include basic physiological aspects of the heart and the strongly connected blood pressure, as well as pathological aspects of blood pressure and the effect of stress on the human body. At the end of this chapter, methods of blood pressure measurement are also addressed.
A more comprehensive explanation of some of the principles and aspects can be found in the literature, especially Pappano and Wier [13], Hall and Guyton [14], and Silbernagl, Kurtz and Pape [15].

2.1 Physiology of the Heart and Ciruclatory System

The circulatory system is a closed vascular system in which blood is pumped through the body by the heart. The blood carries oxygen and nutrients to the cells and removes metabolic waste products [16].

2.1.1 Heart

The heart consists of two pumping systems connected in series, the left ventricle preceded by an atrium and the right ventricle preceded by an atrium. Venous blood reaches the right atrium and subsequently the right ventricle through superior and inferior vena cava. Via contraction of the right ventricle the blood flows into the pulmonary circulation through the pulmonary artery. Here the venous blood is oxygenated. The blood enters the left atrium and thereafter the left ventricle, and via contraction it enters the aorta and subsequently reaches the periphery. Valves between the atria and the ventricles are the tricuspid and mitral valve, they serve as inlet valves. The outlet analogue are the pulmonary and aortic valves leading to the pulmonary circulation and via the aorta to the systemic circulation [14, 15].

The pumping action from the venous to the arterial side is caused by a rhythmic sequence of contraction and relaxation, called systole and diastole. During diastole the ventricles are filled with blood and in the following systole approximately two third of the blood is ejected, called the stroke volume [15]. Figure 2.1 illustrates the structure of the heart and course of blood through the ventricles, atria and valves.
The schematic representation of the conduction system can be seen in figure 2.2. The heart contracts with a frequency of circa 70 beats per minute. The excitation of the contraction propagation starts at the sinus node in the right atrium and is triggered automatically by electrical signals, called action potential. The sinus node consists of specialised heart muscle cells and is considered as the primary pacemaker of the heart. From there, the

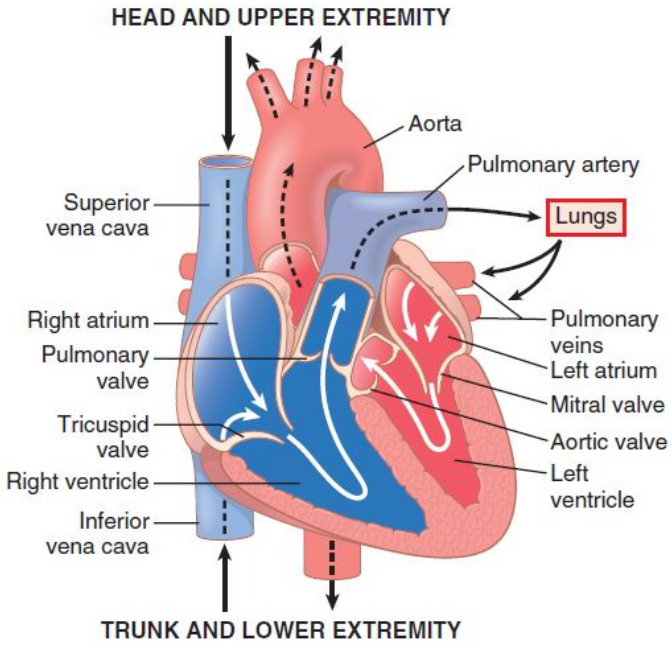


Figure 2.1: Structure of the heart and the blood flow through atria, chambers, and valves [14].

excitation spreads like a fan over the two atria until it reaches the atrioventricular (AV) node. The AV node is located between the atria and ventricles and connects them conductively [15]. It delays the transmission of excitation and allows the ventricles to fill. In the ventricles, the transmission of excitation continues to spread through the His bundle, the ventricular bundle, and via the Purkinje fibres into the ventricular myocardium [14]. As the action potential is the sudden sequence of voltage changes across a cell membrane, an electromechanical coupling between the membrane depolarization triggered by an action potential and the contraction of the structures inside the cell is required [15].

2.1.2 Effects of the Autonomic Nervous System on the Heart Rhythm

The heart is connected to sympathetic and parasympathetic nerve fibres. Sympathetic fibres connect more to the atria and ventricular myocardium and paramsympathetic fibres draw more towards the sinus and AV node. They both adjust the heart rate by altering the activity of ion channels at the sinus node. If the sympathetic nervous system (SNS) is activated, for example by physical activity, there is a positive chronotropic effect, so the heart rate increases. This is achieved by noradrenaline. During parasympathetic activation the opposite effect occurs, i.e. a negative chronotropic effect which leads to the decrease of heart rate. Acetylcholine is released here. In the presence of sympathetic influence, the strength of the heart contraction is also increased, called positive inotropy [15].
In the resting phase, the pacemaker of the heart is under the inhibitory effect of the vagus nerve. SNS and parasympathetic nervous system (PNS) also act on the secondary pacemaker of the heart, the AV node. Here, the release of acetylcholine delays the spread

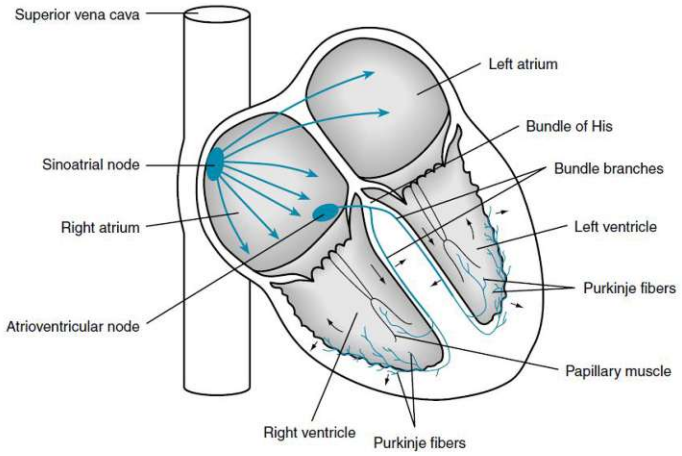


Figure 2.2: Conduction system of the heart in blue with schematic representation of ventricles, atria, and vena cava [13].

of excitation from the atria to the ventricles, defined as a negative dromotropic effect, and norepinephrine accelerates the spread of excitation, defined as a positive dromotropic effect [15].

2.1.3 Circulatory System

The circulatory system consists broadly of arteries, arterioles, capillaries, venules and veins. Arteries transport the blood to the tissues via a high-pressure system. These divide further into arterioles to finally end in the capillaries. Arterioles have a strong muscular layer and can dilate or constrict the vessel by relaxation and contraction. It is at the level of the capillaries where hormones, electrolytes, nutrients etc. are exchanged between the blood and interstitial fluid. Venules collect the blood from the capillaries and transport it back to the heart in increasingly larger veins. Among other things, veins form the low-pressure system and serve as a blood reservoir [14].
The expelled blood is distributed through the vascular system by the pressure difference and reaches the organs. The stroke volume, ejected from the left ventricle, is approximately 70-80 ml, producing a cardiac output of approximately five liters, and a mean pressure of approximately 100 mmHg. This pressure overcomes the total peripheral resistance in the systemic circulation. With a much lower pressure, namely two to four mmHg, the blood arrives in the right atrium, resulting in a pressure difference of 97 mmHg. The two ventricles carry the same amount of blood, but the left ventricle works against a greater flow resistance. Hence, it has a greater workload and muscle mass. Due to systole and diastole, the pressure in the aorta shows a certain course over time. After a pressure maximum, the systolic blood pressure *SBP*, an incisura follows due to the flow reversal. The wave reflection in the periphery of the circulation causes the pressure curve to rise again slightly until the arterial windkessel is exhausted and a minimum is marked, the diastolic blood pressure *DBP*. Larger arteries and the aorta act like a windkessel vessel, meaning they are stretched due to the increasing pressure during the ejection of the stroke volume. The

stored volume continues to flow into the peripheral vessels after the closure of the aortic valve. If the arteries now become stiffer, they can no longer expand well and the windkessel effect diminishes, leading to an increase of the blood pressure amplitude [15]. The *SBP* mainly depends on the stroke volume, the force and rate with which the stroke volume is expelled and the compliance of the aorta and large proximal arteries [17], whereas the *DBP* is primarily determined by the state of the arteries, their capacity to hold the blood outflow from the aorta [18] and the flow resistance of the arterioles [17].

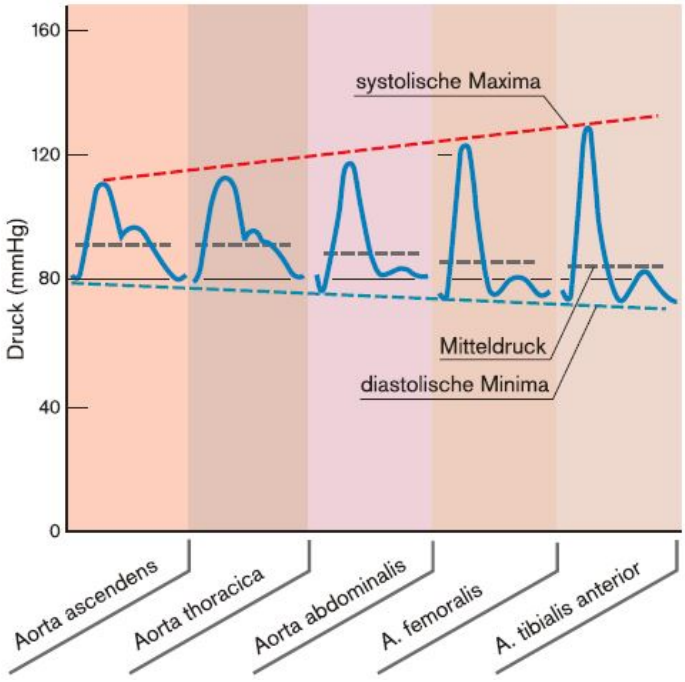


Figure 2.3: Blood pressure waveform changes in the course of some great arteries, with indicated systolic, diastolic, and mean blood pressure [15].

The rate at which the pressure pulse runs through the body is called pulse wave velocity *PWV* and this *PWV* is faster than the velocity of blood itself. The *PWV* varies inversely with compliance of the vessels and directly with the cardiac output. Since the compliance of vessels decreases with the distance from the heart, the shape of the pressure pulse as well as distinctive points on the waveform change with the distance travelled in the arterial system. Further, the forward pulse wave and the reflected pulse wave from the periphery overlap more based on the increasing resistance with decreasing diameter of the vessel. As a result the contour of the arterial pressure wave becomes deformed in the distal part of the arterial system. Several differences can be observed: the waveform becomes steeper, the delay of the pressure rise has lengthened, the incisura is dampened and tends to vanish, and the portion of the systolic pressure becomes slimmer and increases. The distortions of the pressure wave from the aorta to the lower leg with indicated systolic, diastolic, and mean blood pressure are illustrated in figure 2.3. With increasing age, the compliance of the vessels decreases, thus the wave reflections occur faster and the waves superimpose

earlier in time. In addition the alterations of the pressure contour diminish with age [13].

2.1.4 Effects of the Autonomic Nervous System on the Circulatory System

In circulatory regulation, a distinction is made between short-term and long-term regulation and between circulatory functions under stress, physical work, and under thermal stress [15]. However, the regulation of blood pressure is by convention under the concept of homeostasis and states that despite constant perturbation by external stimuli, blood pressure readjusts to a stable value [18].
Short-term regulation consists of stretch receptors in the aortic arch and cartossinus and exhibit a tonic inhibitory influence on sympathetic activity. When arterial blood pressure decreases, this activity decreases and the stroke volume, heart rate and peripheral resistance are increased so that blood pressure rises again. Long-term regulation consists of adjusting salt and fluid intake, and strongly depends on the kidney function. Under physical stress circulatory regulation is initiated with an inhibited parasympathetic nervous system and increased sympathetic activity even before the actual exercise. This happens through neurogenic control processes and is also referred to as the "start reaction". Further characteristic features are increased cardiac output, simultaneously decreased peripheral vessel resistance in the skeletal musculature and vasoconstriction in the remaining organs except the brain to assure the mean blood pressure does not drop [15]. The regulation of the arterial blood pressure is thus a complex interplay of the cardiovascular system, the autonomic nervous system (ANS) and the endocrine system [18].

Regulation of Arterial Blood Pressure

The systolic and diastolic blood pressure are determined by different factors. The *SBP* is mainly dependent on the amount of blood expelled into the aorta with each contraction and on the contraction force, which is determined by the elasticitiy of the aorta. Thus, the *SBP* is primarily determined by the stroke volume and the aortic impedance. On the other hand, the diastolic one depends mainly on the arterial tone and thus, on the total peripheral resistance. If the vessels constrict, the resistance increases and the blood is hindered to flow from the arterial system into the capillaries, thus the *DBP* increases [19]. The difference between the systolic and diastolic blood pressure is the pulse pressure and is mainly ruled by the aortic stiffness and the cardiac performance. Changing one factor will have an impact on the blood pressure. Factors, like the cardiac output and peripheral vascular resistance, are the main determining factors [18].
The cardiac output can be calculated as the product of stroke volume and heart rate, which is governed by sympathetic and parasympathetic input and heart contractility, after-, and preload. The second important factor is the peripheral resistance, driven by contractile arterioles and their nervous impulses from the vasomotor center [18]. The main factors that are essential to vary blood pressure are depicted in figure 2.4.

2.1.5 Hypertension

Cardiovascular diseases (CVD) are the major cause of death, meaning 17.9 million people per year die from CVDs, according to the World Health Organization [1]. Closely inter-

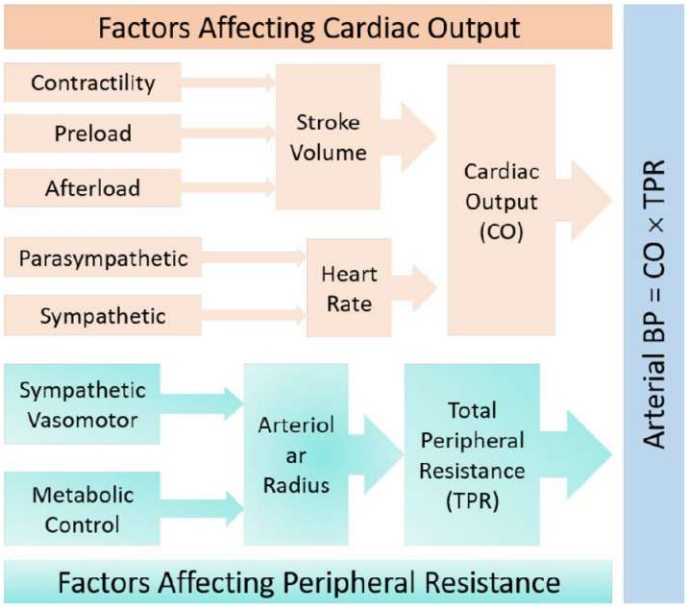


Figure 2.4: Factors affecting the arterial blood pressure [18].

twined is the increased blood pressure, called hypertension. Worldwide, 1.13 billion people are affected by hypertension [1].

Table 2.1: Different categories of hypertension and their corresponding systolic and diastolic values in mmHg [20].

Category	Systolic (mmHg)	Diastolic (mmHg)
Optimal	<120	<80
Normal	120-129	80-84
High Normal	130-139	85-89
Grade 1 Hypertension	140-159	90-99
Grade 2 Hypertension	160-179	100-109
Grade 3 Hypertension	≥180	≥110

Blood Pressure *BP* is classified into optimal, normal, high-normal and hypertension grades one to three according to European Society of Cardiology and European Society of Hypertension (ESH/ESC) guidelines [20], as shown in table 2.1. Thus, hypertension is defined as office systolic blood pressure ≥ 140 mmHg and/or office diastolic blood pressure ≥ 90 mmHg. Office blood pressure (OBP) refers to measuring *BP* in a medical office and distinguishes from home blood pressure monitoring (HBPM) and ambulatory blood pressure monitoring (ABPM), summarised under the term out-of-office blood pressure monitoring. Office and out-of-office monitoring have different thresholds to account for white-coat hy-

pertension (*BP* is higher in the office but normal in HBPM or ABPM), masked hypertension (*BP* is higher in HBPM or ABPM but normal in the office), repeated measurements, automatic devices, manual methods etc. [20].
The underlying aetiology of hypertension depends on the type of hypertension and can have various causes. To maintain the *BP* at physiological levels, several systems are interacting: the renin-angiotensin-aldosterone system (RAAS), the sympathetic nervous system, the immune system, the roles of natriuretic peptides and the role of the endothelium. These systems are summarised unter the term "integrated neurohumoral system". Imbalances or malfunctions in the neurohumoral system affect directly or indirectly the mean blood pressure and blood pressure variability (BPV), and can cause end organ damage. Primary hypertension involves several types of genes and if environmental factors, such as excessive alcohol intake, mental stress or bad sleep quality prevail, the risk for developing hypertension rises. Secondary hypertension is referred to hypertension provoked by another medical condition such as primary aldosteronism or pheochromocytoma [21].

2.2 Blood Pressure Reading

The following methods to determine blood pressure are noninvasive, meaning the skin is not penetrated and thus the risk of infections is nullibiquitous. Nevertheless, invasive measurement methods provide the most precise values. For this purpose, a cannula is inserted into an artery, at the end of which a catheter tip manometer is connected, which measures the pressure in the vessel [15].

2.2.1 Auscultatory and Oscillometric Method

In the auscultatory method, the *BP* is not measured in the aorta but in an artery in the upper arm or thigh. The working principle of the auscultatory method can be seen in figure 2.5. A cuff is placed around the arm and inflated until the pressure in the cuff exceeds the expected systolic pressure. At this time point the distal pulse vanishes, afterwards the pressure in the cuff is then slowly released. If the cuff pressure is between the systolic and diastolic pressure, the Korotkoff sounds can be perceived with a stethoscope. This type of sound is caused by the turbulent flow that occurs when blood re-flows into the partly occluded peripheral vessel during the pressure peaks. Once the cuff pressure drops below the diastolic pressure, the sound becomes quieter and changes from tapping sounds to a muffled one. The *SBP* corresponds to the pressure in the cuff when one starts to hear the tapping sound of the turbulent blood flow. The *DBP* corresponds to the pressure in the cuff when the sound is of muffled quality. Blood pressure data determined with the auscultatory method provide values that are within 10 % of values obtained by direct catheter measurements [14, 15].
This measurement depends on the sound perception of the user, it should be performed under the medical supervision, and is of intermittent nature [6]. In addition, a proper cuff size for the individual arm circumference is essential [5, 22].

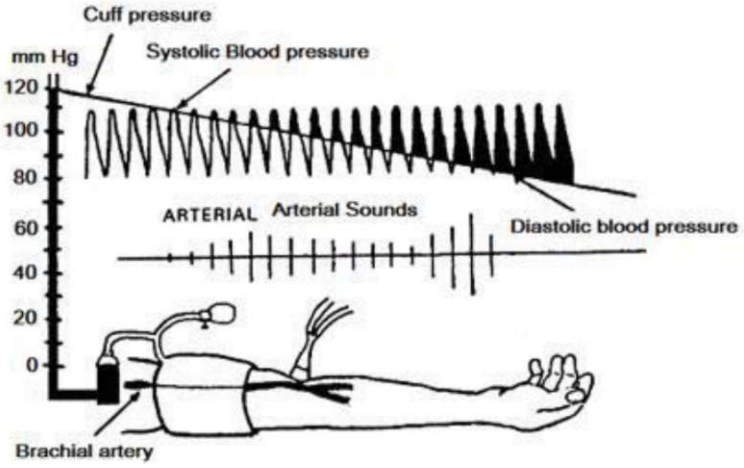


Figure 2.5: Schematic representation of the working principles of the auscultatory blood pressure method with its charactersitic Korotkoff sounds depicted as arterial sounds [23].

Similar to the auscultatory method is the oscillometric method. The working principle of the oscillometric method can be seen in figure 2.6. A cuff is placed around the arms of a patient and inflated also above the expected systolic pressure. Then the pressure slowly decreases until the blood can flow freely. Oscillating pressure pulses from the beat-to-beat blood pulsations of an underneath artery are sensed in the cuff. Those oscillations are overlaid by the decreasing cuff pressure. By separating them, the oscillometric waveform is produced. The peak-to-peak amplitude of the oscillations increases with decreasing cuff pressure, reaches a maximum just about the mean arterial pressure, and drops again. To determine the *SBP* and *DBP* values, several different empirical algorithms can be applied to the waveform [6].
The oscillometric method requires no constant monitoring by medical staff. If a measurement should be performed, the device inflates automatically and records the oscillations for further analysis [24], however data is only available at discrete time points [6]. The right size of cuff is again of importance and depending on the used algorithm and their basic functioning, different systolic and diastolic values may be calculated [22], which can lead to overestimated systolic and underestimated diastolic values [25].

2.2.2 Tonometry Method

With arterial tonometry the waveform of the radial artery is used to determine *SBP* and *DBP*. The shape, duration and amplitude of the waveform provide useful information for diagnoses and disease management and information about forward and reflected wave. For this purpose, a handheld strain gauge pressure sensor is placed orthogonally over the radial artery and mild pressure is applied, leading to the transmission of the arterial pressure to the sensor. The central pressure is then calculated with an algorithm [26].
The applied force to the artery should be constant, not to great to allow the blood flowing in and it should hit directly the center of the artery, to assure correctly calculated central pressures. Despite the fact, that motion interferes with the measurement, it offers a new

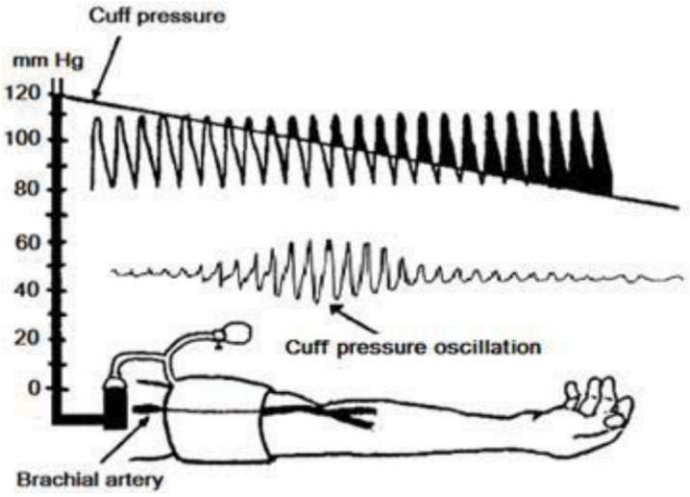


Figure 2.6: Schematic representation of the working principles of the oscillometric blood pressure method with cuff pressure oscillations [23].

method to non-invasively determine blood pressure [6], if the tonometric pressure wave is calibrated with arterial pressure values [27].

2.2.3 Peňáz Volume Clamp Method

The volume clamp method or vascular unloading technique provides continuously and non-invasively blood pressure data using an artery in the finger. Around the finger an inflatable cuff is wrapped with an integrated photoplethysmograph to measure the blood volume changes in this artery. An increase in blood volume and subsequent increase in pressure causes the cuff pressure to increase to maintain a constant artery load/ diameter. The blood volume under the cuff is therefore constant and the continuously changing pressure in the cuff correlates with intra arterial blood pressure [6, 25].
This method needs no constant supervision of medical staff but a constant pressure control which causes this method to be expensive. During longer measurement periods, tissue hypoxia in the figure, where the cuff is wrapped around, may happen. In addition, the volume clamp method relies on perfusion of a certain artery and if medical issues impair the perfusion, the results are not reliable [6].

2.2.4 Continuous Blood Pressure Reading

Blood pressure fluctuates from minute to minute, day to night, through the seasons, and over years and is, amongst other biosignals, the most dynamic one. Those fluctuations are mainly under the maintaining effects of homeostasis and additionally, under the effects of food intake and physical exercise, for instance. A persistent elevation in blood pressure fluctuation may be caused by the effects of an underlying pathological condition associated with dysregulation of humoral and neuronal factors involved in the modulation of cardiovascular function or by intrinsic changes in cardiovascular regulatory mechanisms.

Elevated blood pressure fluctuations have been associated with a higher risk of subclinical organ damage, cardiovascular events, and all-cause mortality. Hence a continuous beat-to-beat blood pressure monitoring over 24 hours would be advisable. The state of the art blood pressure monitoring method is the auscultatory or oscillatory method, which are both discontinuous methods as discussed above and might not reflect the patients true blood pressure pattern [5].
Blood pressure measurements at night provide clinically relevant information, but unfortunately the cuff disturbs the sleep of the person, which can significantly affect blood pressure readings. Conventional 24 hours ABPM, in which *BP* is measured every 15-20 minutes, causes many patients inconvenience, worsens sleep quality and can lead to an increase in nighttime *BP*, resulting in an artificial reduction in the dipping pattern and a subsequent decline in its prognostic significance. These problems complicate the clarification of a number of still open clinical questions, e.g., the actual relationship between obstructive sleep apnoea and hypertension or why heart attacks and strokes mostly occur during sleep and in the early morning. To avoid such inconveniences and to clarify open questions, continuous blood pressure monitoring without a cuff would be necessary. One possible method is the measurement of blood pressure via a catheter inserted into the artery, but this is not proposed for clinical applications due to its invasive nature. The Peňáz method has not found application in clinical practice because of calibration problems and its high cost [5]. A less disruptive approach to monitor blood pressure is based on the analysis of pulse arrival time *PAT* or pulse waves. The next chapters deal with *PAT* and its correlation to *BP*.

2.3 Pulse Arrival Time

Pulse Arrival Time is the time difference between ventricular depolarization and the arrival of the pressure pulse in a peripheral artery [5, 28]. In order to determine *PAT*, different biosignals must be acquired. One signal should correspond to the electrical activity of the heart and another signal should correspond to the peripheral arterial pressure pulse. Closely related to the *PAT* is the pulse transit time *PTT*. The *PTT* quantifies the time difference between two arterial sites, thus it is the time difference between two mechanical signals. It can be determined by the time point of the aortic valve opening and the arrival of this pulse in a peripheral artery or by two different locations along an artery [28, 29, 30]. The *PAT* and *PTT* naturally vary with the input of the underlying physiology and its variation, of which blood is an important element [18].
For the determination of *PAT*, an electrocardiogram for the identification of the onset and a photoplethysmogram for the identification of the peripheral arrival of the pulse are required. In contrast, *PTT* uses either impedancecardiogram, phonocardiogram, seismocardiogram or ballistocardiogram, for the identification of the onset of the pressure pulse and photoplethysmogram to determine the peripheral arrival of the pulse [5]. In the following section the different biosignal acquisitions are briefly explained.

2.3.1 Sensing Elements

- Electrocardiogram (ECG)
  At the interface between excited and unexcited muscle tissue, a potential difference is created, called a dipole, whose electric field spreads throughout the body and can be measured on the surface of the body [15]. The most prominent peak, the R-peak, reflects the depolarization of the ventricles and is usually used as the first fiducial point for determining the PAT [5, 28, 31].

- Photoplethysmyogram (PPG)
  An optical source emits light of a specific wavelength into the tissue of interest, mostly the radial artery, ear lobe, finger or toe. Photodetectors, placed either on the opposite side of the tissue or on the same side as the source, quantify the energy which is partly absorbed or reflected by the underlying tissue and vasculature. The arrived light at the photodetectors consists of static and dynamic components. The static component accounts for 95 % of the signal and constitutes skin, muscle, fat and non-pulsatile blood. The dynamic component accounts for the pulsatile volumetric changes in the vasculature with each heart beat and represents the pulse wave [5]. This method is easy in use and affordable [32].
  The different fiducial points on a PPG, which can be used to determine *PAT*, are stated in the next subsection 2.3.2.

- Impedance Cardiogram (ICG)
  The impedance cardiogram quantifies noninvasively the thoracic impedance and hemodynamic properties by applying high frequency and low amperage electrical current through one of several electrodes to the body of the patient. The remaining electrodes measure the impedance of the underlying vasculature and tissue. Like the PPG signal, the impedance cardiogram consists of static and dynamic components but due to the low resistance of blood, the signal reaches greater depth, and represents the pulsatile blood volume [5].
  A fiducial point on the ICG is the B-point which represents the opening of the aortic valve and can be used to determine the pre-ejection period *PEP* [5, 28]. In essence, PEP accounts for the delay between electrical depolarization and the mechanical activation of the ventricles [5].

- Phonocardiogram (PCG)
  Phonocardiography detects the heart sounds of the closure of the mitral and tricuspid valve (S1), and the sound of the closure of the pulmonary and aortic valve (S2). The two different sound sources are perceived like a "lub dub" in each heart beat [5]. S2 can be used to determine the PEP.

An ECG, ICG and blood pressure or PPG signal is shown in figure 2.7 with labeled *PEP*, *PAT* and *PTT*. From top to bottom, the ECG is shown in green with indicated Q- and R-wave, the ICG signal in blue with zero line and B-point, and at the bottom the blood pressure or PPG signal in red with the fiducial point based on the tangential method. The *PEP* is defined as the time delay between the R-wave and the B-point, the *PAT* is defined as the time between the R-wave and the fiducial point on the PPG signal and thus includes

the *PEP*. The *PTT* is defined as the time between the B-point and the fiducial point on the PPG signal.

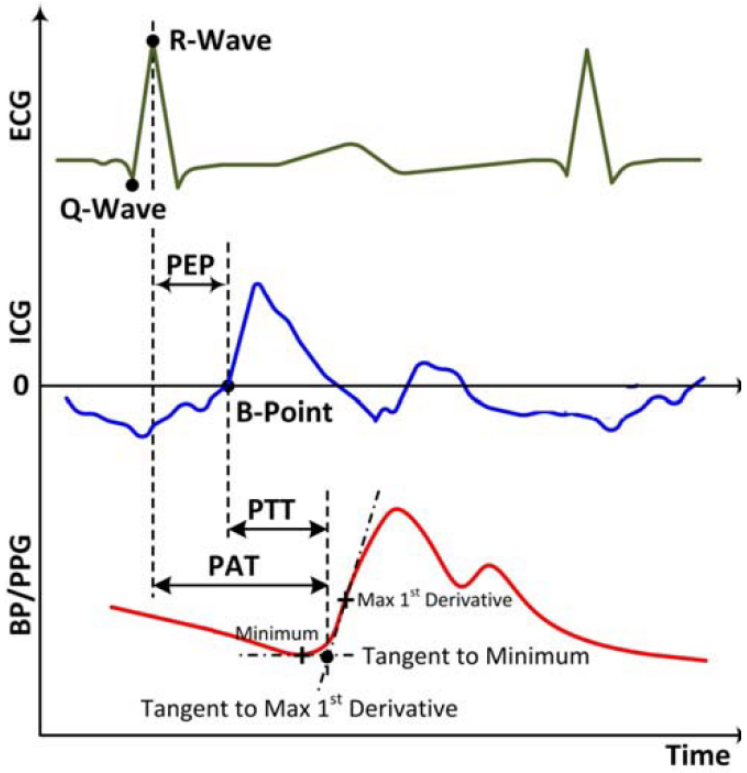


Figure 2.7: Different biosignals are shown along the time axis with *PAT* and *PEP* labeled. Electrocardiogram is shown in green with labled Q- and R-wave, impedance cardiogram is shown in blue with labeled B-point and the pulse wave is shown in red. The time intervals of the *PEP*, *PAT* and *PTT* are shown with their starting and end points [28].

2.3.2 Underlying Physiology

PAT and *PTT* are both related to the *PWV*, which is the velocity at which a pulse pressure wave travels down the arterial tree [5, 18] and a predictor of cardiovascular events and all-cause mortality [33]. The speed of the pulse wave is directly proportional to the blood pressure [31], and it is calculated as the ratio of the length of the segment L and the time the pressure wave needs to travel between two arterial sites *PTT* (equation 2.1) [30]. Using the theoretical equations as for example the Moens-Korteweg equation in conjunction with the empirical Hughes equation, it is possible to determine the relationship between *PWV* and *BP* changes. The Moens-Kortweg equation (equation 2.2) describes the theoretical relation between the interplay of the elastic modulus E at a certain blood pressure P, the thickness of the artery h_0, the radius of the artery R_0 and the density of blood ρ to the pulse wave velocity. The used elastic modulus at a certain pressure P and at zero

blood pressure E_0, and the material coefficient of the artery ζ are then used in the Hughes equation (equation 2.3) to relate PWV to the BP, resulting then in the Bramwell-Hill equation (equation 2.4) [34].

$$PWV = \frac{L}{PTT} \tag{2.1}$$

$$PWV = \sqrt{\frac{Eh_0}{2\rho R_0}} \tag{2.2}$$

$$E = E_0 e^{\zeta P} \tag{2.3}$$

$$PWV = \sqrt{\frac{E_0 h e^{\zeta P}}{2\rho R_0}} \tag{2.4}$$

However, the Moens-Kortweg equation is based on two fundamental assumptions: first, the wall of the artery h is assumed to be a thin shell and secondly, the thickness and radius of the artery remain the same as the blood pressure increases or decreases. Both assumptions do not hold for human arteries. Besides those non-physiological assumptions, the Hughes equation is only of empirical nature with no physiological base [34].

Methods that now rely on PAT measurements rather than PTT measurements attempt to benefit from this relationship by providing a noninvasive, continuous measurement to determine blood pressure values and changes [5]. An increase in blood pressure leads to a rise in vascular tone, thus the arterial wall becomes stiffer and the PAT as well as PTT shorten. The same relationship applies in reverse, if the blood pressure falls due to a decrease in vascular tone, the PAT and PTT lengthen. PAT and PTT changes indicate an inversely proportional relation with blood pressure changes [31]. Yet, classical PAT in itself poses some challenges for comprehensive blood pressure measurements. These include the pre-ejection period, which was already been briefly mentioned above and is described in more detail in section 2.3.2, motion artefacts and hydrostatic pressure errors. The extent of motion artefacts and hydrostatic pressure errors depends on the sensor positioning. For example, if the finger or wrist is used as the distal signal and the sensor is placed above the level of the heart, the actual blood pressure at the site of the sensor will be lower than the blood pressure at heart level and vice versa [5].

Different Locations

To determine the beginning of the pulse arrival time, the R-peak in an ECG is the common starting point and must therefore be detected. For this purpose, for instance, the Pan Tompkins algorithm [35] can be used. Besides the R-peak, the Q-wave can be considered as it represents the beginning of the ventricular electro-mechanical delay, however, the R-wave is easier to detect and more convenient [4].
The determination of the arrival of the pulse wave is not so straightforward, as there are many different possibilities. The proximal and distal waveforms in the arterial system differ not only in time but also in wave reflections. However, since diastolic blood pressure changes only slightly with distance to the periphery, as it can be seen in figure 2.3, wave

reflection interference at the base of the PPG signal does not play a significant role [4]. Thus the foot of the PPG signal or the onset of the rise can be used as a fiducial point. In order to find the onset, the minimum point of the signal and the maximum of the first derivative are searched in the close vicinity of the foot. By intersecting the two tangents to these points, the onset can be determined. With this approach, a high correlation coefficient between *BP*, BPV and *PAT* could be determined [29, 30, 32, 36, 37, 38]. This possibility is shown in figure 2.8 with *PAT* to PPG foot.
Another distinctive point is the systolic peak in the PPG signal. This prominent peak and its resulting time interval from the R-peak can be seen in the figure 2.8 with *PAT* to PPG peak. However, at this point the forward traveling wave and the reflected wave already coincide and can shift the systolic peak in time. It thus may affect the accuracy of *PAT* based applications [38], and is affected by factors that are only marginally related to blood pressure regulation [36].
Regarding the slope of the PPG signal, one can use the maximum rising slope or a midpoint between 20% to 80%, shown in figure 2.8 by *PAT* to PPG slope. Recently, also the second derivative is taken into account to determine the arrival of the pulse [31]. Determination purely on the basis of the slope or a midpoint can lead to distortion due to movement artefacts [39].

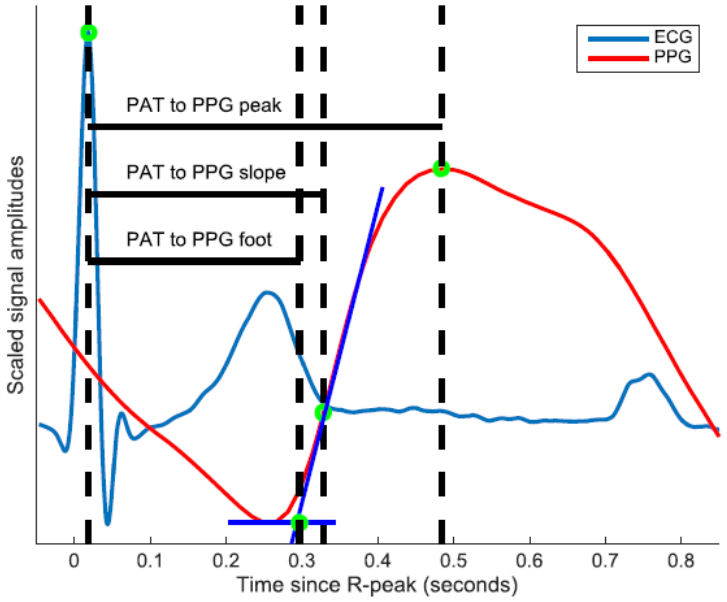


Figure 2.8: ECG signal in blue and PPG signal in red during one cardiac cycle with different indicated points and tangents on the PPG signal and indicated R-peak in the ECG signal [32].

Besides the numerous fiducial points on the PPG signal to determine the pulse arrival in the periphery, there are several different anatomical locations to measure the pulse wave. The most common and popular measurement location is the finger. The finger is already an

integral part of clinical practice by measuring pulse oximetry, for instance, and it is suitable for ambulatory monitoring. Nevertheless, the finger is not the ideal place to measure the arrival of the pulse wave. In people of small stature or women, poor blood flow and low mean blood pressure due to cold stimuli for instance, affects the signal-to-noise ratio, and an accurate and reliable detection of the pulse wave is no longer possible. In addition, measurement on the finger also prevents manual work [28, 31, 32].
Measurement on the wrist with a watch-like device is also under investigation and would be attractive for widespread use. The site is relatively inconspicuous and is already being used to measure other health markers on a smartwatch, for instance. However, orthostatic pressure changes and vasoconstriction are important for a reliable acquisition [32].
A more proximal measurement site would be the ear [28, 31, 32]. The more proximal position has the benefit of being less influenced by vasomotion and orthostatic pressure changes, but could be insensitive to peripheral blood pressure fluctuations [32]. *PAT* or *PTT* measured at the finger and ear, for instance, involves considerable wave travel time through smaller arteries in which smooth muscle contraction and relaxation may result in time delay varying independently of blood pressure [29].
The use of long arterial segments allows more accurate measurements of the *PAT* [40], because small measurement errors in the *PAT* only propagate to small estimation errors in the *SBP*. Thus, PPG measurement on the foot, ancle or toe would reduce the source of errors. However, like in the finger, cold environment would reduce the pulsatile flow and must therefore be taken into account. When measuring PPG on the foot or toe during physical exercise, motion artefacts will interfere with the signal and the signal-to-noise ratio will be degraded [31, 32]. In addition, the development of a portable and convenient system to measure toe or foot *PAT* poses some challenges [29], as it involves inconvenient fixation of the foot sensor, limited accessibility of the measurement method and difficult usage during daily activities [41]. However, Hong and Park [41] managed to measure PPG of the foot sole without constraining the subject or his/ her movement, for instance.

Pre-ejection Period

The pulse arrival time is the time interval between the R-peak in an ECG and a fiducial point in the PPG. The R-peak does not indicate the starting point of the pulse wave from the left ventricle, it solely indicates the ventricular depolarization. The time period between the electrical and mechanical activation is the electromechanical activation time. Once the electromechanical activation time is terminated and the ventricular myocardium is activated, the ventricles starts to contract, but the valves are still closed, hence no blood is expelled. This is referred to the isovolumetric contraction time and in conjunction with the electromechanical activation time, they represent the pre-ejection period *PEP* [5].
The *PEP* is governed by the sympathetic activity, i.e., by the heart rate [42], stress, emotional effort and physical effort, and age [6]. Thus, it does not remain constant. It adapts to the posture of the subject, venous return, hydration status, medications and fluid overload, hence, it represents a source of error. The best solution would be to measure the electromechanical delay, but this can only be achieved by impedance cardiography or phonocardiography in combination with plethysmyography [5]. These examination methods are very expensive, time-consuming, complex, and susceptible to noise, thus using PPG and ECG

is mostly the state of the art [32] and *PEP* is accepted.
PEP constitutes a significant share of *PAT*, ranging from 10 to 35 %, indicating a non-precise relationship between *PAT* and blood pressure [4, 43]. Whether *PEP* has a positive or negative effect on the blood pressure measurement technique based on *PAT*, is controversial [44]. In the review by Ding and Zhang [18], *PAT* measurement that includes *PEP* correlates better with the systolic blood pressure than without *PEP*, although the latter accounts for a substantial proportion.

2.3.3 Pulse Arrival Time based Blood Pressure Applications

The underlying physiological connection between *PWV* and *BP* is already discussed in section 2.3.2 and provides a backbone for *PAT* and *PTT* based blood pressure applications. Several models have been established to approximate the relationship between the *PAT* or *PTT* and the *BP* [5]. Those models are either based on the physical Moens-Kortweg and Bramwell-Hill model or on empirical regression models, where obtained *BP* data are plotted against the calculated *PAT*s. Common to all methods is that one requires reference blood pressure values to compare those values with the obtained *PAT*s and to account for subject specific parameters like the precise relation between blood pressure and the compliance, and the average cross sectional area of the vessel [4]. The different physical models can be looked up in [4, 5, 6, 18] and [44].

A standard approach to assign blood pressure values to pulse arrival time data is as follows: ECG, PPG and blood pressure data are recorded and the pulse arrival time is calculated based on the ECG and PPG signal. A mathematical model that links *PAT* data with *BP* data is defined and the unknown variables in the model must be estimated by fitting the obtained *PAT* and *BP* data to the model [4, 5].
The majority of used models are regression models like linear or nonlinear models [18] and logarithmic, such as equation 2.8 and inverse square models [5]. Linear models disregard a change in arterial thickness and diameter with changing pressure. They are described with their slope a and their intercept b as in equation 2.5 [4, 5]. Nonlinear models are described with two or more unknown variables but may improve the accuracy due to an asymptotic behaviour. Experiments have shown that the inverse of *PAT* or *PTT* is better related to the blood pressure than simple *PAT* or *PTT*, hence models based on equation 2.6 and 2.7 could be also considered [4, 5]. Models containing other factors linked to cardiovascular activity, for instance the heart rate, can be added to improve the robustness of the model, like equation 2.9.

$$BP = a \cdot PAT + b \tag{2.5}$$

$$BP = \frac{a}{PAT + b} \tag{2.6}$$

$$BP = \frac{a}{PAT^2 + b} \tag{2.7}$$

$$BP = a \cdot ln(PAT) + b \tag{2.8}$$

$$BP = a \cdot PAT + b \cdot HR + c \tag{2.9}$$

To obtain the wanted model parameters, *BP* and *PAT* data must be measured simultaneously over a wide blood pressure range. Commonly, physical exercise, e.g., ergometer cycling, orthostatic stress, climbing stairs, Valsalva maneuver, cold pressor or a mental stress test are used to increase or decrease the blood pressure in a physiological range [4, 5, 7, 18]. Bigger changes can be obtained by administering vasoactive drugs via infusion but this is limited to hospitalized patients. The different interventions alter the blood pressure with different physiological mechanisms, thus a calibration curve should be repeated for each individual intervention [4].
The calibration curve should consist of at least one or more *BP*-*PAT* pair than unknown parameters in the model and depends on the subject and its physical state. The more pairs exist, the better the accuracy of the estimation. One of the most popular ways to estimate the parameters is the least square regression [4, 5] and the point-to-point pairing method [45].
Calibration should be done at the beginning of the study and should also be considered to be repeated in a periodical manner, most often every two hours, to improve the accuracy. The measurement intervals are significantly shorter than the time constant relevant to ageing and diseases like artheriosclerosis, however as the *PAT* is determined from the ECG and thus includes *PEP* it is also influenced by a change in vascular tone and smooth muscle contractions. There is also the possibility to perform generalized calibration via the usage of a population average for certain model parameters, however training data must be collected from a wide range of different patients varying in age, diseases, gender, height, etc. [4, 5, 46].
Correlation coefficients between *PAT* and *SBP* are commonly higher for broader blood pressure ranges [4, 30], and during physical exercise [6]. Generally, *DBP* is less correlated to *PAT* than *SBP*, but as its changes are smaller compared to *SBP* changes, the lower correlation coefficient can be expounded [4, 42]. Data from a sleeping study indicate the correlation is superior in sleep than during exercises [28]. The different implications may be due to different methodological designs, different reference methods, etc. [42, 47].

Limitations

PAT alone is not powerful enough to capture all types of blood pressure variations and blood pressure parameters. Several factors besides blood pressure that affect the mechanisms of vascular stiffness make the *PAT* based technique sensitive but not more specific, most notably for peripheral and muscular arteries. The majority of studies use *PAT* as the only variable to infer blood pressure, which results in a wide variety of correlation coefficients that are not constant nor consistent [18, 48]. If systolic and diastolic values change in a different direction, a *PAT* measurement cannot give indication of both values simultaneously, thus the inclusion of additional covariates, for instance the heart rate, like in equation 2.9, would consider this problem [4].
Most studies rely on frequent calibration to maintain tolerable accuracy, as defined in different standards like the Association for the Advancement of Medical Instrumentation (AAMI), British and Irish Hypertension Society (BIHS), European Society of Hypertension (ESH) [49], and Institute of Electrical and Electronics Engineers (IEEE) [50], to be considered for clinical use. This is due to assumptions and simplifications of the Moens-

Kortweg equation for instance, as the arterial dimensions are variables and not constants, they change with each cycle under the vasomotion regulation. Although new calibration methods are already being explored, the fundamental problem remains [18]. If the calibration frequency had to be increased to achieve tolerable values, the *PAT* based approach to measure blood pressure would not be worthwhile as it would not be any simpler or more practical [4].

Pulse arrival time data are a telling indicator of blood pressure changes, especially variability in pulse pressure and systolic blood pressure [36, 43]. They can detect transient or sudden hemodynamic changes [43] and may be used as an additional indicator to detect hypertensive and hypotensive episodes [30]. As the standard ECG and PPG are widely used, the determination of the resulting pulse arrival time in different interventions, such as cardio pulmonary exercise tests, might provide further information on the individual cardiovascular and autonomic response to exercise [51].

2.4 Stress

Relaxation techniques based on physiological coherence, such as Yoga and device-guided slow breathing, and their effect on the cardiovascular system are often the focus of scientific studies [52, 53, 54]. They can reduce the *BP* to a certain degree and thus lengthen *PAT*. However, the effects of different types of stress and their differences on the cardiovascular system on hypertensives or elders, are rarely the focus for scientific studies. For a better comprehension of the impact of stress, it is advisable to take a closer look at stress and its general effects.

2.4.1 Fundamentals

Stress is commonly understood in biological systems as a state that disturbs the homeostasis of an organism, in which an individual is stimulated by an aversive situation [55]. Physiological functions change to respond to the demands of the environment. Since these demands vary constantly, these functions do not truly focus on a certain set point, therefore they are not maintained in the conventional meaning of homeostasis, but instead they vary constantly in order to keep the physiological system stable and to adapt the body to unpredictable external stimuli. The term allostasis can be used for this, which describes stability through change. Thus, there is a link between external conditions and the ability of the body to cope with the challenges they impose [56].
The extent of stress and its physiological sequelae are greatly influenced by how the individual perceives the situation, how they interpret it, and how they perceive their ability to control it [54, 55, 57]. Another essential aspect is the condition of the body itself. Individuals in good physical form can cope with demanding exercise much better than those who are not in shape [57].

The body reacts with the hypothalamic-pituitary-adrenal axis (HPA), the autonomous nervous system (ANS), the metabolic system and the immune system, to the condition of the

body and to the external environment. These systems are closely linked to the psychological state of the individual. Those people who are anxious and reactive will have more reactive physiological responses, while people who have proactive planning capabilities and psychological buffers, will have fewer reactive responses and more stability in their physiology. Systems such as the cardiovascular system, metabolic system and central nervous system, manifest a wide range of activity depending, among others, on external and internal demands. These are part of coping and adaption to a load. These systems are most effective when they can be activated quickly and their activity reduced again, when they are not needed. If this is not case, for example, the systems cannot increase their activity when needed or vice versa, the body will be more stressed and it can compromise health [57].

2.4.2 Stress and its Effects

The general physical and psychological reaction to stress is based on the autonomic nervous system (ANS) and the neuroendocrine system. The sympathetic nervous system gets activated with simultaneous inhibition of the parasympathetic one. In addition, the HPA axis causes the release of epinephrine and norepinephrine, among others [40, 58]. This typically results in a constriction of muscle vessels and increases the peripheral vascular resistance, leading to an increased *BP*, increased oxygen consumption by the heart muscle, reduced beat-to-beat variations of consecutive heartbeats in time (HRV) [59], and to an increase in respiration. As the stress becomes more or unmanageable, adrenomedullary release of the neurotransmitter adrenaline proceeds [60], leading to an increase in *SBP*, a decrease in *DBP* and an increase in heart rate *HR* [61].

Since the *HR* changes with stress, the resulting HRV exhibits also changes. In principle, HRV is said to reflect the balance between sympathetic and parasympathetic influences on the intrinsic rhythm of the sinus node, responsible for the heart rate. The extent of HRV provides information about the ability of the heart to respond to environmental changes. Increased HRV generally indicates a healthy heart, whereas decreased HRV indicates a weakening of the ability of the autonomic nervous system to respond to changes [9, 59]. Some selected measures of the HRV are the standard deviation of all normal-to-normal intervals *SDNN*, corresponding to the overall variability and it depends on the length of the signal [62, 63], and the root mean square of successive normal-to-normal interval differences *RMSSD* which estimates the short-term components of HRV and reflects vagal nerve activity [59, 62]. In addition, one measure from the frequency domain is the ratio of low frequency to high frequency power. *HF* component reflects vagal activity and its band is ranging from 0.15 - 0.4 Hz. There is disagreement about the *LF* component and its band ranging from 0.04 - 0.15 Hz, because it is understood on the one hand as a quantitative marker for sympathetic modulations and on the other hand as a measure of sympathetic as well as vagal activity. Consequently, the *LF/HF* ratio is seen by some as the sympathovagal balance or as a reflection of sympathetic modulations [62]. An increased ratio suggests sympathetic dominance and a decrease parasympathetic dominance [63].

Physical Stress

During low intensity exercise, the *HR* increases nearly exclusively through vagal withdrawal. Above the steady state of exercise intensity, there is an increase in sympathetic activity. At the onset of exercise, venous return is increased by the pumping action of the skeletal muscles and stroke volume increases via the Starling mechanism. The arterial pressure and heart rate increase in a parallel manner at the beginning and during exercise, indicating a resetting of the arterial baroreflex. Resetting the working point of the arterial baroreflex upwards seems to be the main contributing factor to the sympathetic excitatory response and the increase in blood pressure during exercise [64]. Related to this, HRV is also reduced, *SDNN* and parasympathetic activity related *RMSSD* and *HF* values fall with physical exertion. *LF/HF* shows different trends with physical exertion, as they are also calculated differently in most studies [63] but an increase, i.e. a shift in the direction of the sympathetic nervous system, would be expected [65].
An early recovery of heart rate after exercise is dominated by vagal reactivation, while sympathetic withdrawal gains importance later in the recovery phase. As heart rate recovers, so does HRV. In the first minutes there is a rapid but not complete recovery and it can take up to 48 hours for a complete recovery, with overshoot periods in the 48 hours [63]. The rate at which heart rate returns to baseline after exercise is found to be related to fitness and health and is usually calculated from the peak of exercise to the first or second minute of recovery. A declined recovery rate, possibly due to reduced vagal activity, is a powerful predictor of all-cause mortality, regardless of workload and presence or absence of myocardial perfusion defects [64].

Mental Stress

Mental stress tests commonly consist of either mirror tracing tests, Stroop tests, mental arithmetics or speech delivery tasks. Psychological stress reactions to these or similar tests in healthy people include cardiovascular reactivity [12]. This involves an increase in *HR*, *BP*, sympathetic outflow, circulating levels of epinephrine, adrenocorticotropic hormone and cortisol [12], and an increase in sympathovagal balance [66]. There is usually a sustained rise in central systolic pressure and pulse pressure, while mean pressure usually does not change significantly. This is accompanied by a sustained increase in *PWV*, suggesting an increase in aortic stiffness [11, 58].
Since sympathetic activity is also increased during mental stress, HRV parameters exhibit also changes. An elevation in the *LF* component and a reduction in the *HF* component can be observed [65]. Thus, *RMSSD* shows also a decrease but once the mental stress is over, *SDNN* and *RMSSD* values increase again, pointing to increased paramsympathetic activity and relaxation [67].

The stiffness of the large arteries and arterial wave reflection are important determinants of coronary blood flow, left ventricular function, and arterial mechanical integrity, thus, they are involved in the pathogenesis of systolic hypertension. Catecholamine release and endothelial function are regulators of arterial stiffness and wave reflection and are associated with acute mental stress. Augmentation pressure, which is the pressure added to

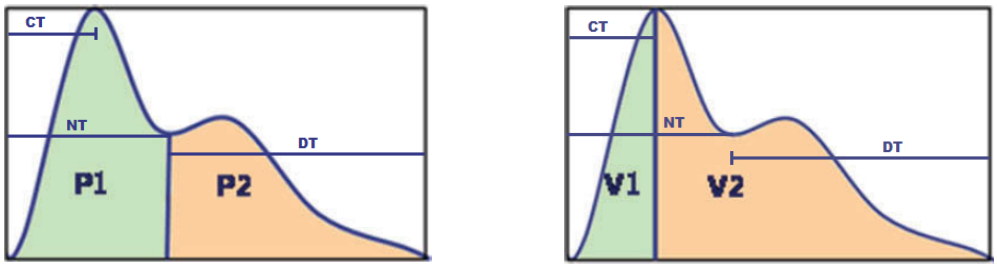
the incident wave by the returning wave, and augmentation index, which is the ratio of augmented pressure and the pulse pressure, show a persistent increase with mental stress. In cases where reflected waves return late to the ascending aorta, as is the case in young normal subjects, they merge with the incident wave in the diastole, increasing the diastolic fraction and facilitating coronary perfusion. If the reflected waves return earlier due to increased stiffness and are amplified, they merge with the incident wave in the early systole and amplify the systolic portion. In this way, not only is the diastolic portion of the waveform not increased and coronary perfusion not facilitated, but left ventricular afterload is also increased, leading to increased oxygen demand and an unfavourable supply/demand relationship in the myocardium [11].
Higher reactivity and lower recovery from psychological stress lead to a sustained stress response [33] and are associated with subsequently poor cardiovascular risk status [33, 66]. Commonly, increased reactivity is associated with hypertension, atherosclerosis, myocardial ischaemia or myocardial infarction [11, 68]. In particular, the magnitude of the increase in blood pressure in response to psychological stress is prognostic for the severity of myocardial ischaemia [12].

2.4.3 Stress Monitoring

Mental stress is harmful to cardiovascular health, as it is a risk factor for coronary heart disease and a trigger for cardiac events, however it is not currently routinely studied [69]. Accordingly, reliable markers measuring psychological stress or load could be used to monitor stressful conditions in daily life and it would enable accurate monitoring of patients, prevent disease, detect pathological conditions in early stages, as well as be a tool for mental health and well-being [70].
Because the response to stress triggers a variety of cognitive, physiological and hormonal responses that result in a wide range of changes in the body, a single stress marker cannot provide a generalised assessment of the stress response [70]. Several techniques are currently used to assess stress levels, but these are limited to intermittent measurements, often requiring a trained operator, and are not suitable for continuous monitoring, for instance measuring cortisol hormone levels from saliva or urine, and stress questionnaires. Stress can also be assessed using cardiovascular parameters like *BP*, *HR*, HRV, respiratory parameters and galvanic skin response [40, 70, 71, 72].
From a physiological perspective, the PPG signal is a powerful source of information because it is influenced by the cardiac, vascular and the sympathetic nervous system, which are all affected by stress. For example, changes in *BP*, *HR* or HRV can be expected to influence the PPG signal [69]. Consequently, several aspects of the PPG signal may change with stress [71] and it provides a potentially effective and convenient method of assessing psychological stress [69]. The peripheral arterial tone changes with mental effort and results in peripheral vasoconstriction, which again is reflected in the PPG appearance [72, 73].

PPG signals provide a variety of features that are able to reflect the changing trend caused by stress [73]. For instance, according to the studies of Celka et al. [71] and Arza et al. [70] changes in the crest time *CT*, the time from pulse onset to the systolic peak, and notch

time *NT*, time from onset to the dicrotic notch, were observed in the presence of stress. The *CT* and the *DT* are influenced by a variety of cardiovascular characteristics, such as heart rate, stroke volume, left ventricular ejection time and systemic vascular resistance. During stress the *CT* and *DT* decrease, due to the increase in heart rate and decrease in left ventricular ejection time, and they increase during relaxation. The *CT*, *DT*, and the *NT* can be seen in figure 2.9.
Features depending on either the *CT* or *DT* also show a trend during stress, like the pulse arrival time or the inflection point area *IPA*. *IPA* is the ratio of area under the pulse wave during diastole (from the dicrotic notch to the end of the pulse wave) and systole (from the onset of the pulse wave till the dicrotic notch) [69, 71]. Figure 2.9a illustrates the *IPA* with the corresponding equation 2.10. Similar to the IPA is the stress-induced vascular response index *sVRI*, shown in figure 2.9b and equation 2.11. It is again the relative ratio of two areas from the PPG waveform, one being the area from the onset to the systolic peak and the other being the area from the systolic peak to the end. As mental effort and stress increases, the *sVRI* increases [72]. The *sVRI* is interpreted as an indicator of wave reflections and vascular tone and compared to HRV parameters, which takes at least two minutes to process, the *sVRI* is more accessible and calculable [73].



(a) PPG waveform with resulting *IPA*

(b) PPG waveform with resulting *sVRI*

Figure 2.9: (a): *IPA* calculated as the ratio of area under the curve from onset to dicrotic notch (P1 green) and from dicrotic notch to the end (P2 orange). Adapted from [73].
(b): *sVRI* calculated as the ratio of area under the curve from onset to systolic peak (V1 green) and from systolic peak to the end (V2 orange). Adapted from [73].

$$IPA = \frac{P2}{P1} \tag{2.10}$$

$$sVRI = \frac{V2}{V1} \tag{2.11}$$

Beside questionnaires and cardiovascular parameters, PPG features, especially *CT*, *DT* and either *IPA* or *sVRI*, should be added to stress evaluation and monitoring.

3 Methodology

In this thesis, the effect of mental stress and physical exercise on several cardiovascular parameters in hypertensive patients are investigated using a new device. The next chapters include patient demographics, the measurement protocol, a description of the used device, the approach for pulse arrival time determination as well as the determination of the other cardiovascular parameters, and the description of post-hoc analyses.

This study was conducted in July 2020 by the Austrian Institute of Technology (AIT) in collaboration with the center for interdisciplinary medicine, diagnostics and therapy in Dortmund, Germany, under the medical supervision of Dr. med. Walter Sehnert.

3.1 Subjects

Fifty-two patients with treated arterial hypertension participated in this study on a voluntary basis. They were informed in written and verbal form about the study procedure and gave their written consent. The protocol of the study was approved by the ethics committee of the Medical Association of Westphalia-Lippe and the University of Münster ("Ethik-Kommission der Ärztekammer Westfalen-Lippe und der Westfälischen Wilhelms-Universität Münster", file reference 2017-733-f-S) on 15 March 2018.

Sociodemographical data and health characteristics were examined from each participant, before the measurement procedure started. They are listed in table 3.1. Sociodemographics included their age and sex, and health characteristics included their office blood pressure classification ranging from normal to grade 2, since when they suffer from hypertension, what drugs they have been prescribed, their quantities, and whether they had been diagnosed with any other cardiovascular diseases, such as left ventricular hypertrophy, arteriosclerosis, or others. In addition, *SBP* and *DBP* of the subjects were also recorded at the beginning of the study sessions and are listed in the table. The absolute amount of subjects performing a physical stress test or a mental stress test are as well stated in the table. Values in the table 3.1 are either absolute numbers or mean with standard deviation in brackets.
52 subjects (31 male, 21 female) ranging between 40 and 81 years with a mean age of 64.6 years were either assigned to the physical or mental test. The third gender was neglected because none of the subjects identified with it. Out of the 52 subjects 28 performed the mental task and the remaining 24 the physical one. Not all patients suffered from arterial hypertension, a large share, 22 out of 52, were classified as normal in the blood pressure classification, as they were well treated with medication. Blood pressure class high normal and grade 1 formed the bulk along with the normal blood pressure class, solely one subject was classified with hypertension grade 2. The mean time since they suffer from

Table 3.1: Summary of demographical data and health characteristics from the participants. Data are either absolute numbers or mean values with standard deviation in brackets.

	N
Participants (#)	52
Age (years)	64.6 (8.2)
Gender (#/#)	31 males / 21 females
Task (#/#)	28 mental / 24 physical
Arterial Hypertension since (years)	14.9 (9.5)
Solely Arterial Hypertension (#)	8
Hypertension normal (#)	22
Hypertension high normal (#)	13
Hypertension Grade 1 (#)	16
Hypertension Grade 2 (#)	1
Number of Drugs	2 (1)
Systolic Blood Pressure (mmHg)	129.0 (14.5)
Diastolic Blood Pressure (mmHg)	78.6 (10.5)

arterial hypertension was 14.9 years, however the standard deviation of 9.5 years indicated a wide range. On average, patients were prescribed two medications to treat hypertension, six out of 52 did not take any medication. Medications ranged from Angiotensin-converting enzyme (ACE) inhibitors, Angiotensin receptor blockers, beta blockers, Calcium channel blockers to diuretics. The majority of subjects, namely 44 out of 52, were diagnosed with more than only arterial hypertension. The mean *SBP* stood at 129.0 mmHg and the *DBP* at 78.6 mmHg, indicating an overall elevated blood pressure and validating the hypertension or elevated blood pressure of the subjects. There was no information about the timing of the menstrual cycle or menopause of the female participants.
Out of the original 52 enrolled subjects with 78 recorded measurement sets, two subjects were excluded due to the loss of their measurement sets, refer to figure 3.1. From the remaining 50 subjects, another two participants were excluded because their data were of too poor quality. With the remaining 48 subjects the evaluation was carried out. The larger number of measurement series than subjects can be attributed by the fact that sometimes a new measurement had to be started if the patient did not feel well, a measurement error occurred or no data was transmitted from the device.

3.2 Protocol

Once the patients arrived, they were provided with information about the study and the task. After giving their consent, the patients were given time to acclimatise in a quiet, temperature-controlled room and to familiarise themselves with the measurement device and get used to holding it. The protocol consisted of four different segments, baseline 1, baseline 2, task and recovery, each lasted for approximately five minutes. The flow chart of the study can be seen in figure 3.2.
In the first baseline period, the device continuously recorded and stored ECG and PPG

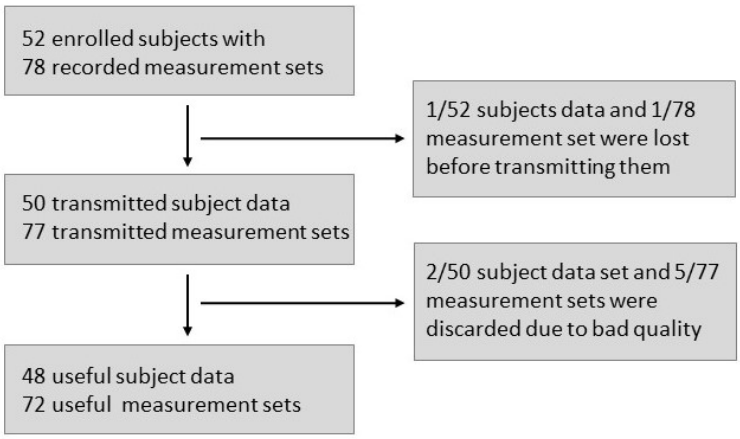


Figure 3.1: Data exclusion with the number of included subjects and measurement sets. A measurement set comprises ECG and PPG waveforms.

data for a total of five minutes. After the first, second and third minute in the first baseline period, blood pressure was determined oscillometrically using the WatchBP Office (Microlife AG Swiss Corporation, Switzerland) device [74]. This was done simultaneously for the left and right upper arm. The second baseline segment also consisted of continuously recording ECG and PPG data for five minutes. Blood pressure was again determined oscillometrically after the first, second and third minute, but only on the left upper arm. After the second baseline period, the task followed. During the task, ECG and PPG data were again continuously recorded but blood pressure was not determined, as it would have lead to more artefacts, for example, and as the subjects should not experience any further impairments. The randomly assigned task was either of physical or of mental nature and is described in more detail in the sections 3.2.1 and 3.2.2. After the task, the recovery period followed. During this period, ECG and PPG data were continuously recorded for five minutes and the blood pressure on the left arm was recorded after the first, second and third minute. If the patient felt good after one of the first three segments, the measurement was not stopped but the measurement for the next segment was continued immediately. In order to allocate the data to the right protocol segment afterwards, the start and end times of the respective segments were noted to the seconds.

3.2.1 Physiological Stress Task

Subjects to whom the physical stress test was allocated went down the staircase to the underground car park directly after the second baseline period and without a break back up the staircase to the examination room. Oscillometric blood pressure was not measured during the task. The next blood pressure measurement was taken during the recovery phase after the first minute. During the task, however, ECG and PPG data were measured with the handheld device. As some participants had to take a short break while others completed the task in a very short time, the length of this segment is not exactly five minutes.

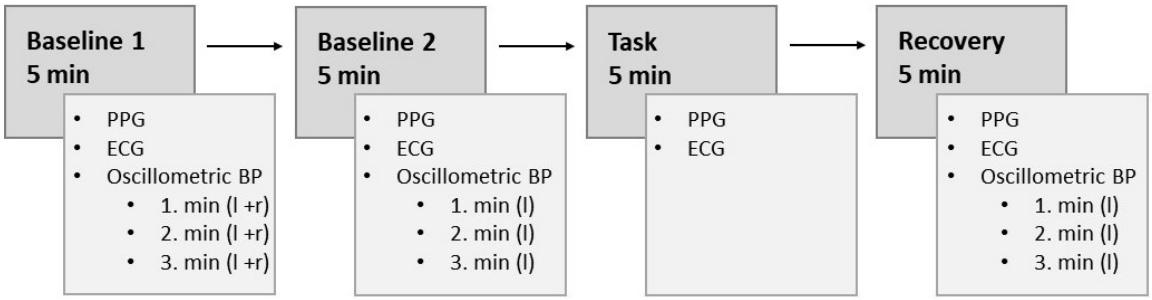


Figure 3.2: Study protocol consisted of four different segments, Baseline 1, Baseline 2, Task, and Recovery, each lasting approximately five minutes. ECG and PPG data were continuously recorded and oscillometric blood pressure data was recorded, apart from during the task, after the first, second and third minute either left and right (l+r) or left (l) only.

3.2.2 Mental Stress Task

Subjects to whom the mental stress test was attributed had to perform a modified DemTect test [75]. This test originally consists of five parts: word list/delayed recall, number transcoding, verbal fluency, digit span and again the word list/delayed recall. In the word list, a list of ten words should be immediate recalled in two trials at the beginning and the end of the test. Maximum achievable points are 20, and at the end of the test, when it is repeated, ten. During the number transcoding task, arabic numerals should be converted into verbal numerals and two verbal written numerals should be converted into arabic numerals. Maximum achievable points are four. In the verbal fluency task, subjects should name as many items that can be bought in a supermarket within one minute. Maximum achievable points are 30. And in the digit span task, subjects should repeat digits in reverse order up to a maximum length of six. Maximum achievable points are six [75].
For this study, number transcoding was transformed into adding the digits of two four to five digit numbers. The modified DemTect test can be found in the appendix A.1. The points achieved per subject were added up and noted. Similarly to the physical stress task, the length of the segment varies a little.

3.3 Device

The smartPWA, standing for smart Pulse Wave Analysis, device is a bio-signal acquisition sensor device specially developed and built by the AIT Austrian Institute of Technology (Vienna, Austria) for research projects. The device is intended to be held by the user with both hands, like a gamepad, as shown in figure 3.3. It uses three conductive surface areas that are touched by the user with their thumbs and left index finger to acquire a standard Einthoven I lead ECG. Furthermore, the right index finger of the user touches an optical sensor for PPG to measure blood volume changes in the microvascular bed of the finger.
The ECG and PPG signals are converted from analog to digital signals at 256Hz and

24-bit resolution. Communication with a smartphone or tablet computer is established via Bluetooth low energy (BLE) and the measured signals are streamed continuously to a mobile app for further data processing. A precursor study using this device is currently being written.

Figure 3.3: SmartPWA device with the left index finger and both thumbs of the user on ECG surface areas and right index finger on PPG surface area. Developed and built by the AIT (Vienna, Austria).

3.3.1 Data

Raw ECG und PPG data were transmitted from the device and saved as a text file (txt). A counter, which served as a timestamp, was also saved with the data. However, calculated timestamps from the device have always startet at zero, thus the exact determination of the beginning and end of a segment to the second is not possible. A maximum offset of one minute is given.
Sociodemographic data and health characteristics of each participant, start time and end time of the measurement, as well as notes and comments on the measurements were transferred from the study as an Excel file. The data were read into Matlab, processed and analysed.

3.4 Post-hoc Analysis

Pulse arrival time, heart rates, heart rate variability parameters and pulse wave features were determined. They are described in the following section.

3.4.1 Calculation of the Pulse Arrival Time

There are several ways to determine *PAT*, as mentioned in section 2.3.2. In this study, *PAT* was determined using an ECG and PPG signal. The PPG signal served to record the distal pulse wave and the ECG signal served to record the proximal pulse wave, since other methods such as impedance cardiography or phonocardiography could not be embedded in such a mobile and handy device, and ECG and PPG signal determination are better suited for daily use.
The timing of the proximal pulse wave was defined by the R-peak in the ECG signal. It was determined using an in-house developed algorithm. The timing of the arrival of the distal pulse wave was measured at the beginning of the rising edge, which can be obtained by intersecting tangents [76]. Figure 3.4 illustrates the intersecting method to determine the onset of the distal wave. A tangent is placed at the point of the signal with the largest gradient and at the minimum of the signal as well. The point where the two tangents meet, which is called intersection point, is used as the onset point.

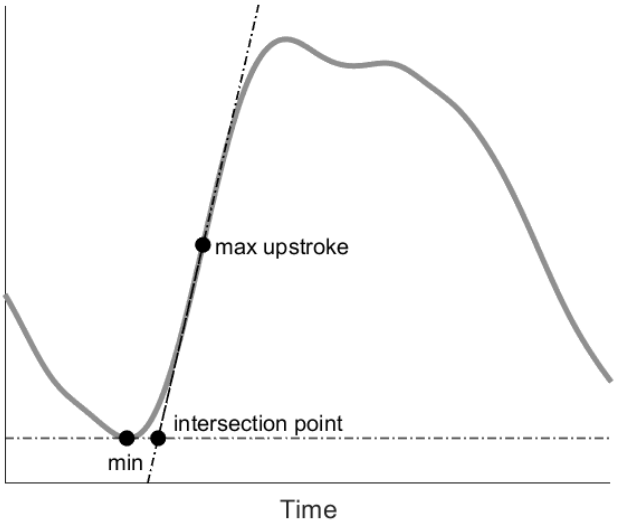


Figure 3.4: Method to determine the onset of the pulse wave. The line through the minimum point of the pulse wave and a tangent through the point with maximum systolic ustroke were intersected, resutling in the onset of the pulse wave.

Figure 3.5 shows the time difference between the ECG R-peak, highlighted with a dashed line, and the onset of the distal pulse wave, highlighted with a solid line, resulting in the *PAT*. Blood pressure could not be determined with the specific *PAT* data, as there were too few blood pressure data per subject to develop a reliable correlation model.

Determining the pulse arrival time via the R-peak in the ECG is the most simple way, but it includes the pre-ejection period, which is the time between the electrical excitation and the mechanical ejection (see section 2.3.2). The pre-ejection period could not be calculated explicitly in this work because only ECG and PPG data were available as continuous data.

Furthermore, seeing the pre-ejection period as a constant and simple subtracting it, would also be wrong, as it changes with the human physiology.

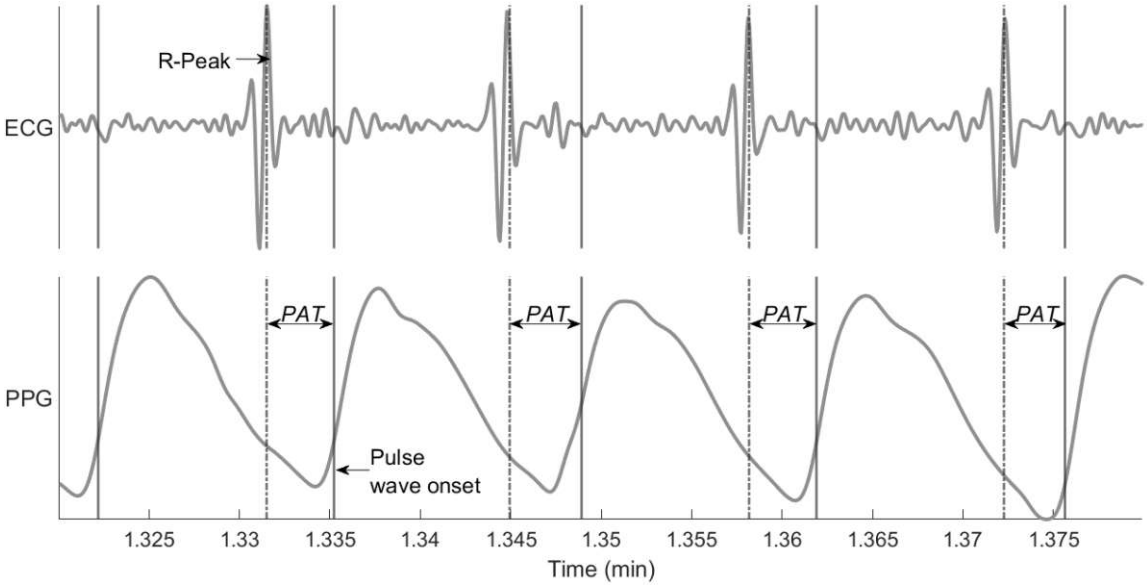


Figure 3.5: ECG and PPG recordings during a short time span with highlighted R-peak in the ECG (dashed line) and highlighted onset of the pulse wave (solid line). The difference between these two time point is the *PAT*.

3.4.2 Pulse Arrival Time and Heart Rate

Pulse arrival time data and heart rate were determined for each heartbeat during all four segments for all subjects. The heart rate was calculated from the distances between the consecutive R-peaks in the ECG, taking the reciprocal value from it and converting it to beats per minute by simply multiplying with 60.
To detect outliers, the recorded signals were filtered based on the criteria stated by Suzuki et al. [77]. If the heart rate was under 30 or over 200 beats per minute, pulse arrival time and heart rate were removed. Neighboring data points to the deleted ones were also removed. In addition, the time between successive R-peaks could not change by any more than 0.2 seconds, or the corresponding *PAT* and *HR*, and their neighboring data points were also removed [76, 77]. In addition, data values of the *HR* and *PAT* above 1.5 of the median of the respective *HR* or *PAT* and below 0.5 of the median were detected as outliers and removed for further processing. By averaging over the length of each segment, which was roughly five minutes long, short-term fluctuations such as the influence of breathing or movement artefacts were reduced. At least four pulse arrival time and heart rate values must have been present in the window (one protocol segment), or the data was discarded. Thus, one *PAT* value and one *HR* value for each segment and each subject were calculated.

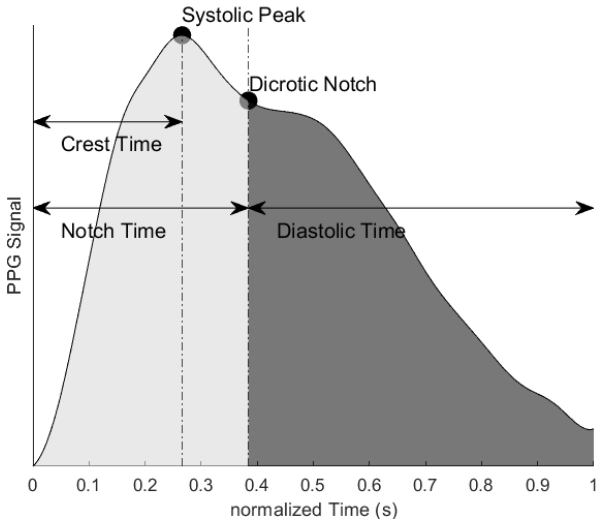
3.4.3 Heart Rate Variability

Furthermore, heart rate variability parameters were also calculated. These include the standard deviation of normal-to-normal intervals *SDNN*, root mean square of successive normal-to-normal interval differences *RMSSD* and the ratio of the spectral power in the low frequency band, ranging from 0.04 to 0.15 Hz and the high frequency band, ranging from 0.15 to 0.4 Hz *LF/HF*. Spectral analysis was performed using the Lomb Scargle Periodogram. Commonly, HRV data are determined based on five minute-recordings [62] to ease standardisation of different studies. Theoretically, this would work out well with the length of each segment, however, as some subjects completed the task faster or required more time, the times also varied. The shortest segment was therefore selected and HRV data was evaluated based on the shortest length to produce uniform data. The shortest segment was around two minutes long and thus information only of the high and low frequency bands could be accounted for. The shorter signal period, might also reduced the calculated SDNN values, since it depends on the length of the signal [62]. Besides the shortening of the signal for the HRV analysis, the resulting parameters were averaged within this short signal length to reduce short-term fluctuations.

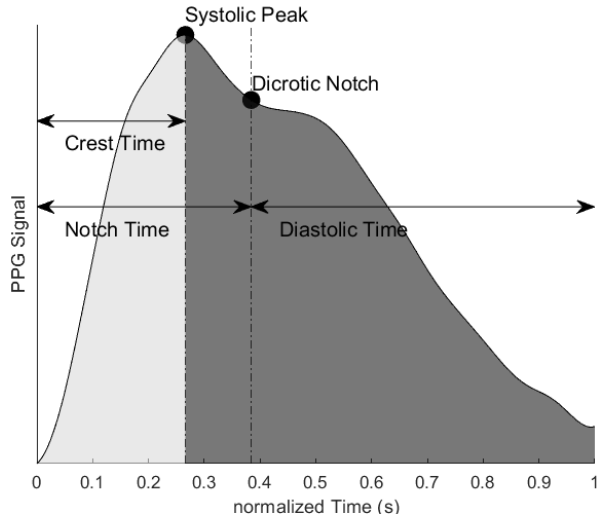
3.4.4 Pulse Wave Characteristics

Apart from the *PAT*, *HR* and HRV data, pulse wave characteristics were also evaluated, based on the paper from Celka et al. [69, 71]. They include the crest time *CT*, the duration of the diastole *DT* and the inflection point area *IPA*. In addition, the notch time *NT* and the stress-induced vascular response index *sVRI* [72] were also calculated.

The crest time is defined as time from the pulse wave onset to the systolic peak, the notch time is defined as the time from the wave onset to the dicrotic notch, and the duration of the diastole is defined as the time from the dicrotic notch to the end of the pulse wave. These pulse wave characteristics can be seen in figure 3.6. Furthermore, the inflection point area is the ratio of the area under the pulse wave during diastole (dark grey in figure 3.6a) and systole (light grey in figure 3.6a), and the stress-induced vascular response index is the ratio of the area under the pulse wave during diastole starting from the systolic peak (dark grey in figure 3.6b) and the systole (light grey in figure 3.6b). The duration of the diastole, crest time and inflection point area are said to respond to an increased stress [69, 71]. For the determination of the different parameters, each pulse wave was normalized to the length of one second and the signal was filtered with a finite impulse response filter (FIR). In addition, *IPA* and *sVRI* were searched for outliers and if detected, they were removed. If at least four pulse wave characteristics could have been calculated in the window, corresponding to one protocol segment, the average was calculated over the length of each segment. If less than four values were in the window, the data was discarded.



(a) Pulse wave signal with indicated inflection point area *IPA*.



(b) Pulse wave signal with indicated stress-induced vascular response *sVR*.

Figure 3.6: (a): Pulse wave signal with indicated *CT*, *NT*, *DT* and *IPA*; ratio of area under the pulse wave signal during diastole (dark grey) and systole (light grey).
(b): Pulse wave signal with indicated *CT*, *NT*, *DT* and *sVRI*; ratio of area under the pulse wave during diastole (dark grey) starting from systolic peak and systole (light grey).

3.4.5 Plots

The results were plotted as functions over the four segments mostly as boxplots. In order to remove also the subjects intervariability, the first baseline value was subtracted from the last recovery value, and the difference was evaluated and plotted as boxplots.
Since the sample population consisted of different tasks, age groups, genders and diagnoses,

all determined parameters were also divided into different groups, i.e. into the task nature, either physical or mental, into male and female, into older or younger than the average, and into the different blood pressure classifications. Consideration was given not to include more than three groups, allowing statistical tests to be carried out without compromising the validity of the results. If a parameter could not be calculated for one of the four phases but could be calculated for all other three, the data set was not used. Plots that are not presented in the results are included in the Appendix.

3.4.6 Correlation

Correlation between evaluated parameters was also investigated, such as the correlation between *SBP* or *DBP* data and the determined *PAT* and the inverse relationship. For this purpose, either the difference between averaged baseline values and averaged recovery values of *PAT* and the difference of first and last *SBP* and *DBP* data were calculated and then their correlation was calculated, or the averaged values were considered. The correlation between *PAT* and *HR* was also performed, but their averaged values were considered for this purpose, not their differences.

3.4.7 Statistical Evaluation

All data values were tested for normal distribution using a two-sided goodness of fit Lilliefors test, where the parameters of the null distribution are estimated [78]. The null hypothesis stated that the data was from a normal family and the alternative that they did not come from a normal family.
To calculate statistical significance at a 5 % level between the different measurements, either a paired-sample t-test or a Wilcoxon signed rank test was applied. The paired-sample t-test was applied when the data came from a normal distribution and the Wilcoxon signed rank test was applied when the data did not come from a normal distribution. The data sets had to be of equal size and a Bonferroni correction was applied to reduce the alpha error summation [79].
For statistical evaluation of the difference between the beginning and the end of the measurement, i.e. to find out whether the differences are significantly away from the zero line, the data was tested either with a paired-sample t-test or again with a Wilcoxon signed rank test. The p-values were again corrected with the Bonferroni correction.
In order to evaluate data sets of different subjects, either a two-sample t-test or a Wilcoxon rank sum test was applied. The two-sample t-test was applied when the data came from a normal distribution and the Wilcoxon rank sum test was applied when the data did not come from a normal distribution.
In addition to the 5 % significance level, statistical significance at a 1 % level and 0.1 % level were determined and highlighted with asterisks. One asterisk corresponds to $p < 0.05$, two asterisks correspond to $p < 0.01$ and three asterisks correspond to $p < 0.001$.
Data coming from a normal distribution were reported as mean and their standard deviation (SD). Data not coming from a normal distribution were reported as median and their interquartile range (IQR).

4 Results

In this section *SBP*s, *DBP*s, *PAT*s, *HR*s, *LF/HF* power ratios, *SDNN*s, *RMSSD*s, *CT*s, *DT*s, *NT*s, *IPA*s and *sVRI*s are examined in general and afterwards in the different groupings. Differences between the groups, for example between the mental task group and the physical task group, as well as differences between the phases, for example between baseline and task, will be investigated. How the parameters behave between the beginning and the end of the recordings, whether they increase or decrease significantly, is also examined here, as well as correlations between the parameters.
Due to the data situation and data quality, it was not possible to use the same subjects to determine each parameter, since some data sets contained too many outliers, some parameters could not be calculated or other factors. This made it difficult to compare the individual parameters, but otherwise the data sets would have been too small and no statistically significant statements could have been drawn from it.

4.1 General Time Course

At first the different calculated parameters during both baselines, the task and the recovery are shown as boxplots. In addition, if the data were normally distributed, the means and standard deviations are listed and if the data were not normally distributed, the medians with first and third quartiles are listed. No distinction is made here based on the nature of the task, the sex of the subjects, the age of the subjects neither on their blood pressure grade. In addition to examining any differences between the phases, it was also evaluated whether there was a decrease or increase of the parameters between the beginning and end of the measurement, that was statistically significant.
The breakdown of the individual participants, how many are male and female, etc., is shown in the table 4.1.

Table 4.1: Breakdown of the participants based on the task, sex, age and blood pressure classes.

$\sum$	**mental**	**physical**	**male**	**female**	**younger** age $<$ 64.6 years	**older** age $>$ 64.6 years	**BP normal**	**BP elevated**	**BP grade 1**
48	26	22	28	20	22	26	21	12	15

All parameters and the number of used measurement sets are listed in the table 4.2. As already described in section 3.4.7, data belonging to a normal distribution are represented with mean and standard deviation (mean (SD)) and non-normally distributed data are represented with median and interquartile range (median [IQR]).

Table 4.2: Means with standard deviations in round brackets, medians with interquartile ranges in square brackets and number of used measurement sets of the different parameters during both baselines, the task and the recovery.

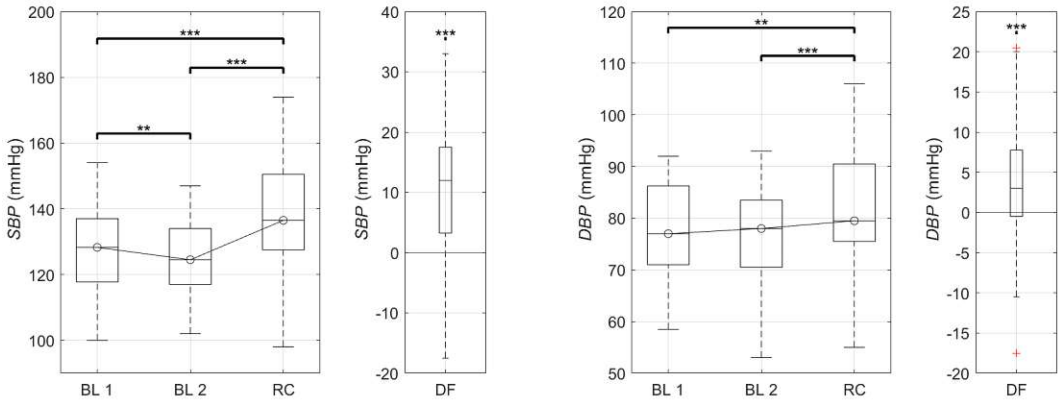
	Baseline 1	Baseline 2	Task	Recovery	N (#)
SBP (mmHg)	127.94 (12.68)	124.89 (11.64)	-	139.00 (17.46)	48
DBP (mmHg)	77.71 (9.09)	76.45 (8.77)	-	81.53 (11.37)	48
PAT (ms)	262.56 (35.45)	256.81 (31.86)	236.10 (44.32)	248.13 (37.76)	37
HR (1/min)	71.57 (12.12)	70.80 (11.93)	89.69 (21.25)	75.37 (13.14)	45
LF/HF (1)	1.32 [0.50, 2.11]	1.35 [0.73, 1.61]	2.24 [1.56, 3.29]	2.22 [1.47, 2.77]	25
SDNN (ms)	31.39 [26.23, 48.32]	32.14 [25.12, 42.40]	38.53 [25.57, 58.12]	47.33 [34.93, 64.67]	43
RMSSD (ms)	31.82 [25.52, 43.32]	31.59 [27.47, 42.54]	29.95 [25.87, 45.80]	34.07 [28.01, 42.63]	37
CT (ms)	282.46 (51.31)	281.52 (47.94)	332.08 (78.47)	295.27 (55.83)	43
DT (ms)	579.66 (60.03)	578.52 (57.48)	495.93 (94.85)	551.64 (69.53)	43
NT (ms)	420.33 (60.03)	421.48 (57.48)	504.07 (94.85)	448.36 (69.53)	43
IPA (1)	0.86 (0.26)	0.87 (0.25)	0.56 (0.24)	0.71 (0.23)	43
sVRI (1)	2.20 [1.95, 2.58]	2.27 [1.95, 2.47]	1.67 [1.46, 2.12]	2.02 [1.72, 2.30]	43

4.1.1 Blood Pressure

Systolic and diastolic blood pressure were only measured during both baselines for three times and during the recovery phase again for three times. The data were normally distributed according to the Lilliefors test, thus mean values with standard deviations were calculated and are listed in table 4.2.
The corresponding boxplots of systolic and diastolic blood pressures can be seen in figure 4.1a and figure 4.1b. The left plot shows always the boxplot with averaged values and the right plot shows the difference between the first baseline and the recovery phase. All of the usable subjects recordings, 48 out of 52, could be included in the generation of these two boxplots.

There was a highly significant increase ($p < 0.001$) of the *SBP* from the first baseline and the second baseline to the recovery phase. A significant decline ($p < 0.01$) between the two baselines could also be observed. The direct comparison of *SBP* values before and after the task showed a highly significant increase ($p < 0.001$), on average 12 mmHg.

A similar trend could be observed in the *DBP*, only the level of significance was slightly decreased from first baseline to recovery ($p < 0.01$). A significant difference between both baselines could not be observed here, but a highly significant increase from the beginning to the end of averaged three mmHg could also be seen here.



(a) *SBP* (mmHg) (b) *DBP* (mmHg)

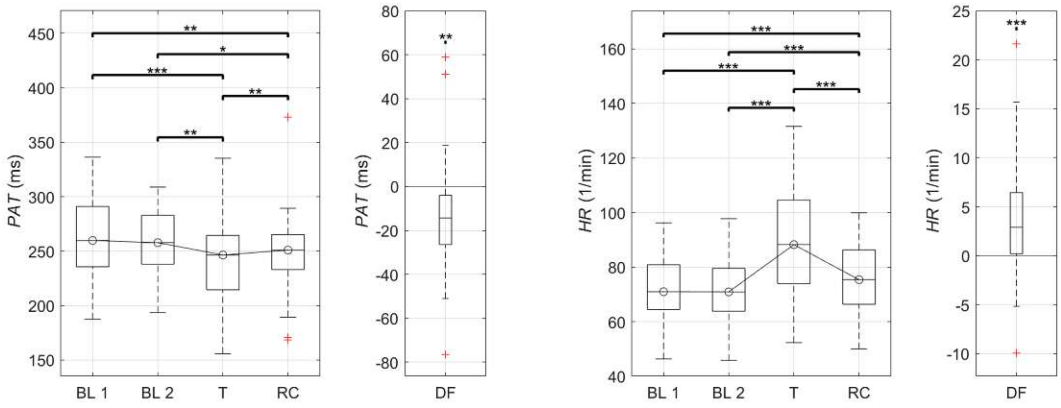
Figure 4.1: Boxplots of averaged *SBP*s (mmHg) and *DBP*s (mmHg) at both baselines (BL1, BL2) and at the end (RC). Single boxplot difference (DF) of first baseline value to recovery value. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.1.2 Pulse Arrival Time and Heart Rate

Pulse arrival times and heart rates were measured continuously during each segment. Both parameters were normally distributed according to the Lilliefors test, thus mean values with standard deviations were calculated and are listed in table 4.2.
The corresponding boxplots of pulse arrival times can be seen in figure 4.2a and heart rates in figure 4.2b. Not all subjects recording were usable for the generation of the boxplots, as major outliers were excluded.

*PAT*s decreased during the task and slightly increased again in the recovery phase. There was a significant difference between the *PAT*s during the task compared to both baselines (BL1 $p < 0.001$, BL2 $p < 0.01$) and recovery ($p < 0.01$). There was also a significant difference between the *PAT*s in the recovery phase compared to both baselines (first baseline $p < 0.01$, second baseline $p < 0.05$). *PAT*s during the first and second baseline periods showed no significant difference. In the direct comparison of *PAT*s before and after the task (right plot in figure 4.2a), a significant decline ($p < 0.01$) of 14 ms on average was observed. For the determination of *PAT*s 37 out of 48 subjects measurement sets could be included.

A highly significant difference ($p < 0.001$) existed between the *HR*s during the task compared to both baselines and recovery and also between the *HR*s during the recovery to both baselines. By the end of the recovery phase (right plot in figure 4.2b), the heart rate rose highly significantly by an average of three beats per minute. A total of 45 out of 48 usable subjects measurement sets were included for the calculation of the *HR*, the remaining had to be excluded due to outliers or due to bad signal quality.



(a) *PAT* (ms) (b) *HR* (1/min)

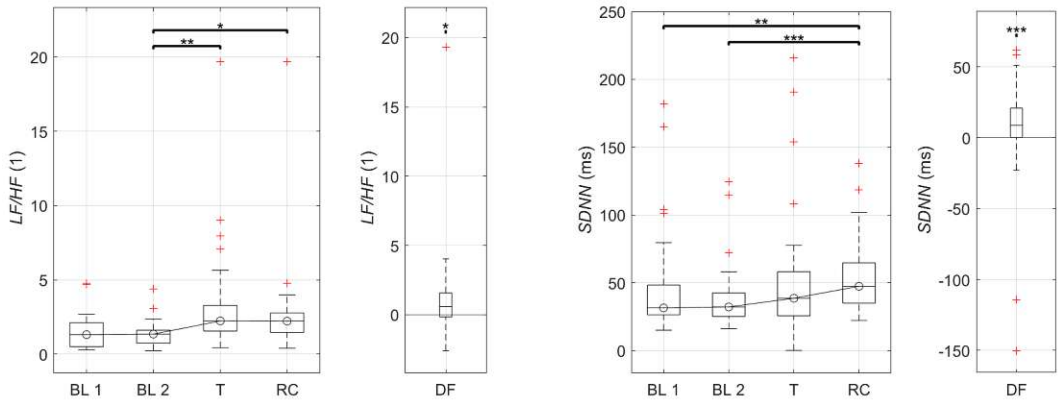
Figure 4.2: Boxplots of averaged *PAT*s (ms) and *HR*s (1/min) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Single boxplot difference (DF) of first baseline value to recovery value. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.1.3 Hear Rate Variability

In analogy to the parameters already mentioned, heart rate variability parameters before the task, during the task and after the task were also examined, including *LF/HF* power ratio, *SDNN* and *RMSSD*. They were not normally distributed and therefore, their medians, first and third quartiles were calculated and can be found in table 4.2.
The corresponding boxplots of *LF/HF* power ratios can be seen in figure 4.3a, *SDNN*s in figure 4.3b and *RMSSD*s in figure 4.4. Not all subjects recordings were usuable for the generation of the boxplots, as major outliers were excluded and HRV parameter calculations required a minimum signal quality, which was sometimes not achieved.

Only 25 subjects measurement sets could be included in the calculation of the *LF/HF*s. An increase in the *LF/HF*s over the course of the experiment could be seen. At the beginning, the values were low and significantly increased ($p < 0.01$) during the task and stayed elevated. There is a slight significance ($p < 0.05$) between the second baseline phase and the recovery phase. Towards the end, a slightly significant increase between the beginning and the end of 0.6 could be observed (right plot in figure 4.3a).

In the course of the study, highly significant increases were found in the *SDNN*s in the recovery phase in relation to the first two baselines. The rise of *SDNN*s could already be seen during the task, when looking at the connected medians, however with no significance. There existed a mid-significant increase ($p < 0.01$) from the first baseline to the recovery and a highly significant increase ($p < 0.001$) from the second baseline to the recovery. The *SDNN* increase from beginning to the end was again highly significant ($p < 0.001$), on average nine ms (right plot in figure 4.3b). In total, 43 subjects measurement sets could be used for the calculation of the *SDNN*.



(a) *LF/HF* (1) (b) *SDNN* (ms)

Figure 4.3: Boxplots of the averaged *LF/HF*s (1) and *SDNN*s (ms) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Single boxplot difference (DF) of first baseline value to recovery value. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

RMSSDs during the study showed no significant differences. The connected medians in the boxplot implied a small decrease during the task and a minor increase after the task. The direct comparison of baseline to recovery revealed a slightly significant increase ($p < 0.05$) in *RMSSD*s, on average three ms (right plot in figure 4.4). A total of 37 subjects recordings contributed to the calculation of the *RMSSD*.

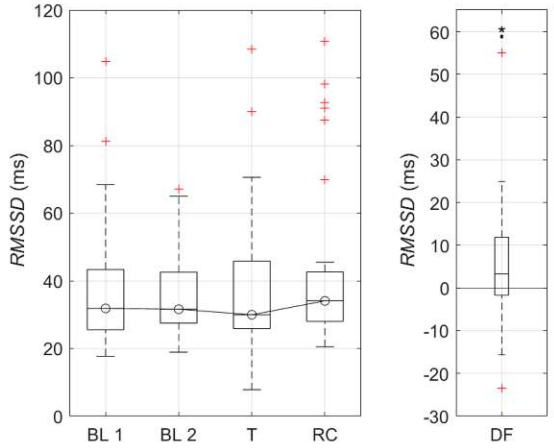


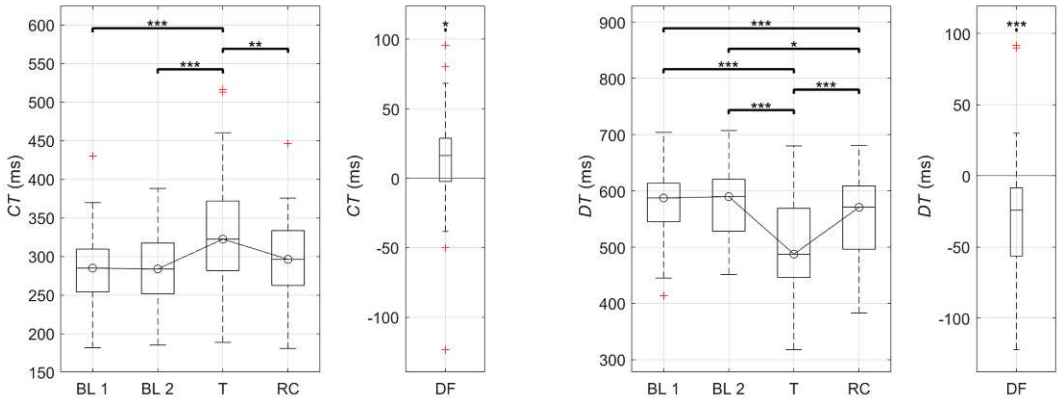
Figure 4.4: Boxplots of the averaged *RMSSD*s (ms) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Right: Difference (DF) of notch time at first baseline to recovery. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.1.4 Pulse Wave Characteristics

Five different pulse wave characteristics were calculated based on literature research, three of them are the following: the time from the beginning of the pulse wave to the systolic peak CT, duration of the diastole DT and the time from dicrotic notch to end of the pulse wave NT. Those parameters were normally distributed, thus their mean values and standard deviations were calculated and are listed in table 4.2. The remaining two parameters, inflection point area and stress-induced vascular response index, are described after the different pulse wave times.
The corresponding boxplots for CTs can be seen in figure 4.5a, DTs in figure 4.5b and NTs in figure 4.6. For their calculations, 43 out of 48 measurement sets were included in each case.

CTs increased highly significantly ($p < 0.001$) from the first and second baseline to the task and fell significantly ($p < 0.01$) after the task. The comparison of the final CT value with the initial value in the right plot in figure 4.5a, showed a slightly significant rise ($p < 0.05$), on average CT increased by 16 ms compared to the initial value.

The duration of the diastole behaved opposite to the crest time, it decreased during the task and increased afterwards again but did not return to the initial value. Between DTs during the task and both baselines and between the task and the recovery were highly significant differences ($p < 0.001$). Significant differences between the DT in the recovery period with both baselines were also evident. The recovery values decreased highly significantly ($p < 0.001$) in relation to the first baseline and slightly significantly ($p < 0.05$) in relation to the second baseline. By the end of the recovery phase, the duration of the diastole had decreased highly significantly by an average of 24 ms (right plot in figure 4.5b).



(a) CT (ms) (b) DT (ms)

Figure 4.5: Boxplots of the averaged CTs (ms) and DTs (ms) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Single boxplot difference (DF) of first baseline value to recovery value. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

The notch time behaved similarly to the crest time and thus oppositely to the duration of the diastole. During the task, NT increased highly significantly ($p < 0.001$) compared to the first and second baseline as well compared to the recovery phase. NT from the second baseline in relation to the recovery increased also, however with only a slight significance ($p < 0.05$). A highly significant increase from the first baseline to the recovery phase was also evident, on average 24 ms (right plot in figure 4.6).

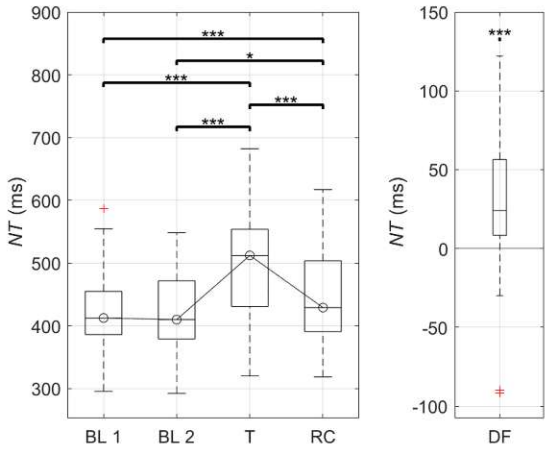


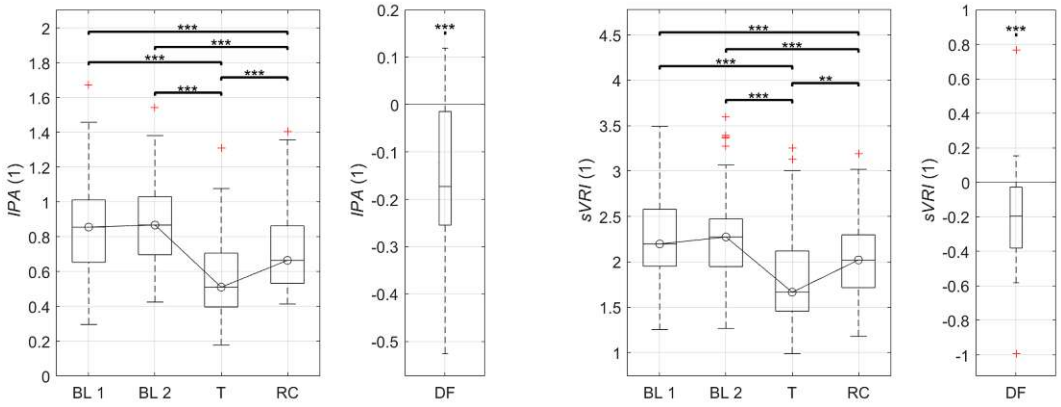
Figure 4.6: Boxplots of the averaged NTs (ms) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Right: Difference (DF) of notch time at first baseline to recovery. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

Besides the crest times, durations of the diastole and notch times, inflection point areas IPA and stress-induced vascular response indices $sVRI$ were also calculated. IPA values were normally distributed, so their mean values and standard deviations were calculated and since sVRIs were not normally distributed, their medians, first and third quartiles were calculated and are listed in table 4.2.
The corresponding boxplots of IPAs are shown in figure 4.7a and $sVRI$s in figure 4.7b. Here again, not all useful measurement sets could be included in the calculations of IPAs and $SVRI$s.

The IPA, the ratio of area under the diastole curve to the area under the systole curve, showed also significant changes during the measurement. During the task, IPA decreased and afterwards increased again in the recovery phase, both with statistically high significance ($p < 0.001$). However, the direct comparison from the beginning to the end in the right plot in figure 4.7a exhibited that IPA could not regain the initial value, its final value was highly significantly lower ($p < 0.001$). For the determination of the inflection point area 43 subjects measurement sets could be included.

A similar trend prevailed with the stress-induced vascular response index. During the task, $sVRI$ fell highly significantly ($p < 0.001$) and increased afterwards again ($p < 0.01$). Also, the direct comparison of baseline and recovery phase in the right plot in figure 4.7b shows

the fall of *sVRI* during the measurement, again with high significance ($p < 0.001$). For the determination of the *sVRI*, again 43 subjects measurement sets could be included.
Compared to the *IPA*, *sVRI* had a wider range of variation. Since these two parameters are very similar, the rest of the thesis will no longer deal with both parameters, but only *IPA*.



(a) *IPA* (1) (b) *sVRI* (1)

Figure 4.7: Boxplots of the averaged *IPA*s (1) and *sVRI*s (1) at both baselines (BL1, BL2), during the task (T) and at the end (RC). Single boxplot difference (DF) of first baseline value to recovery value. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.2 Task

In the following section, the subjects population was divided into the nature of the task, in either physical or mental task. In addition to examining any differences between the groups, it was also evaluated whether there was a decrease or increase in the calculated parameters of the groups between the beginning and end of the measurement, that was statistically significantly different from zero. Not all parameters will be described here, only those that exhibited a statistically significant or an interesting progression. The remaining plots are shown in the Appendix A.2.
All in all, 48 measurement sets could be used, comprising 22 physical task and 26 mental task. A more detailed breakdown of the 48 participants is shown in table 4.3.

Table 4.3: Breakdown of the participants according to the nature of the task and further breakdown into gender, age and blood pressure classes.

	$\sum$	**male**	**female**	**younger** age < 64.6 years	**older** age > 64.6 years	**BP normal**	**BP elevated**	**BP grade 1**
mental	26	17	9	11	15	11	6	9
physical	22	11	11	11	11	10	6	6

All useful and further described parameters with the number of used measurement sets

for the group, who performed the mental task and the physical, are listed in the table 4.4. Data belonging to a normal distribution are represented with means and standard deviations (mean (SD)) and non-normally distributed data are represented with medians and interquartile ranges (median [IQR]).

Table 4.4: Means with standard deviations in round brackets, medians with interquartile ranges in square brackets and number of used measurement sets of the different parameters during both baselines, the task and the recovery for the mental and physical group.

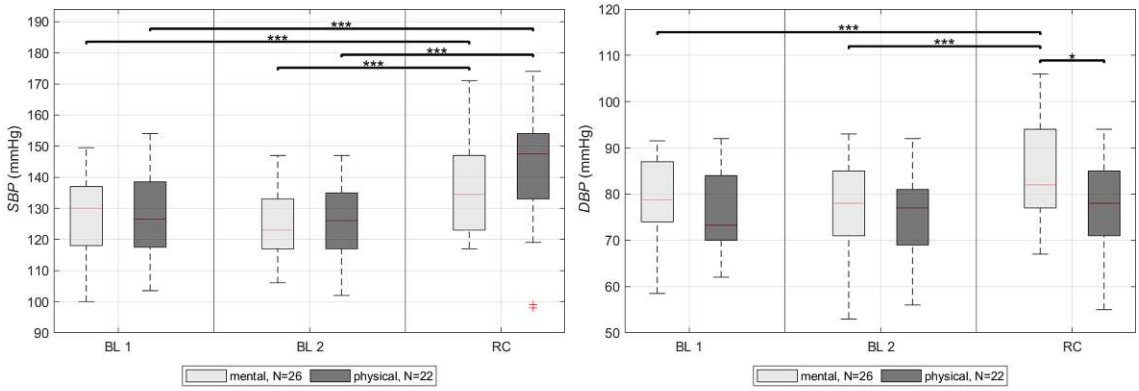
		Baseline 1	Baseline 2	Task	Recovery	N (#)
SBP (mmHg)	mental	127.86 (12.11)	124.84 (10.37)	-	136.16 (15.31)	26
	physical	128.02 (13.59)	124.95 (13.19)	-	142.23 (19.47)	22
DBP (mmHg)	mental	78.22 (9.17)	77.36 (8.80)	-	85.16 (10.85)	26
	physical	77.14 (9.17)	75.41 (8.81)	-	77.41 (10.73)	22
PAT (ms)	mental	261.01 (33.26)	255.31 (31.91)	251.70 (38.24)	255.25 (39.91)	24
	physical	265.43 (40.47)	259.59 (32.89)	207.30 (41.29)	235.00 (30.59)	13
HR (1/min)	mental	71.13 (12.61)	70.96 (12.40)	75.58 (13.05)	73.15 (12.33)	25
	physical	72.13 (11.79)	70.60 (11.63)	107.34 (15.51)	78.14 (13.90)	20
LF/HF (1)	mental	1.07 [0.46, 2.14]	1.35 [0.71, 1.58]	2.20 [1.46, 2.90]	2.22 [1.43, 2.91]	19
	physical	1.63 [0.99, 2.10]	1.39 [1.18, 1.83]	2.92 [1.94, 7.98]	2.27 [1.99, 2.53]	6
SDNN (ms)	mental	32.46 [26.33, 47.78]	31.66 [24.70, 44.56]	40.72 [31.73, 57.82]	40.72 [31.58, 57.82]	23
	physical	31.04 [25.63, 52.53]	32.88 [25.88, 42.22]	34.09 [10.21, 58.43]	48.56 [39.05, 77.68]	20
RMSSD (ms)	mental	28.55 [25.39, 43.20]	30.89 [26.57, 43.74]	29.93 [26.79, 41.67]	34.10 [27.88, 41.62]	23
	physical	32.23 [25.63, 43.09]	33.21 [28.08, 39.42]	31.61 [24.31, 51.74]	32.72 [28.66, 69.83]	14
CT (ms)	mental	269.99 (50.16)	272.90 (48.00)	297.04 (61.82)	290.29 (56.62)	23
	physical	296.80 (50.02)	291.44 (47.11)	372.37 (77.42)	301.00 (55.79)	20
DT (ms)	mental	594.18 (55.05)	587.22 (55.33)	549.39 (74.61)	560.88 (69.29)	23
	physical	562.98 (62.53)	568.52 (59.67)	434.45 (77.48)	541.01 (70.03)	20
NT (ms)	mental	405.82 (55.05)	412.78 (55.33)	450.61 (74.61)	439.12 (69.29)	23
	physical	437.02 (62.53)	431.48 (59.67)	565.55 (77.48)	458.99 (70.03)	20
IPA (1)	mental	0.87 (0.28)	0.88 (0.27)	0.69 (0.22)	0.75 (0.23)	23
	physical	0.86 (0.24)	0.87 (0.23)	0.40 (0.16)	0.68 (0.24)	20

4.2.1 Blood Pressure

Blood pressure values divided according to the task nature were both normally distributed, hence, mean values and standard deviations were calculated and are listed in the table 4.4.

Figure 4.8a shows the systolic blood pressure in the mental and physical group as grouped boxplots. *SBP* between the mental and physical task group did not show significant differences. In both baseline periods of the groups, the blood pressure behaved very similar. Medians of the physical groups were slightly higher, but the same increasing trend toward the recovery phase, as seen in the general part, was evident. Considering the groups individually, each recovery phase was statistically highly significant ($p < 0.001$) above the two

baseline phases. The decrease of the second baseline value in the systolic blood pressure, already described in the general part, could only be observed in the mental group, but without significance. Overall, there was a highly significant increase ($p < 0.001$) in *SBP* in both the mental and physical groups between the beginning and the end of the experiment. The physical group increased slightly significantly ($p < 0.05$) more than the mental group.



(a) *SBP* (mmHg)

(b) *DBP* (mmHg)

Figure 4.8: Grouped boxplots of blood pressures (mmHg) during both baselines (BL1, BL2) and at the end (RC) for mental and physical tasks. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

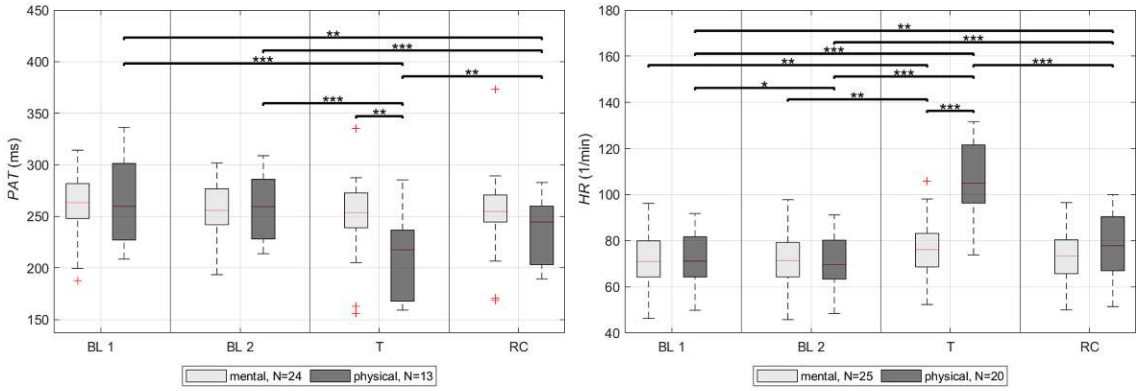
Figure 4.8b shows the diastolic blood pressure in the mental and physical group as grouped boxplots. There was a slightly significant difference ($p < 0.05$) in the recovery phases, such that the mental task group exceeded the physical one. During both baselines the medians of the physical group were marginally increased. When looking at the groups separately, only the mental group showed a highly significant increase ($p < 0.001$) from both baselines to the recovery phase. In the physical group, the recovery phase showed no significant differences to the baselines. For the mental group, there was a highly significant increase ($p < 0.001$) in *DBP* between the beginning and the end of the experiment, while for the physical group, there was only a slight statistically insignificant increase ($p < 0.05$). Their changes throughout the experiment were significantly different ($p < 0.01$), i.e. *DBP* after the mental task increased overall more than *DBP* after the physical task.

4.2.2 Pulse Arrival Time and Heart Rate

Pulse arrival times and heart rates divided according to the task nature were normally distributed, therefore, their mean values and standard deviations were calculated and are listed in the table 4.4.

Pulse arrival times from mental and physical groups as boxplots are shown in figure 4.9a. The direct comparison of the *PAT*s of the physical and mental group showed a significant difference ($p < 0.01$) during the task phase, with the physical task dropping the *PAT* more than the mental one. During the recovery phase, the median of the physical group remained

below that of the mental group, however, in the baseline periods both groups behaved quite the same. Considering the individual groups separately, the following observations could be made. In the mental group there were no significant differences, as the *PAT*s remained the same on average during all phases. Despite this, the initial value could not be reached again. In the physical group, however, significant differences occurred. *PAT*s during the task decreased highly significantly ($p < 0.001$) compared to both baseline periods and increased significantly ($p < 0.01$) at the recovery phase. In the recovery phase, the baseline values could not be regained as well. Both groups showed a significant decrease in *PAT* between the beginning and the end of the recording (mental group $p < 0.05$, physical group $p < 0.001$). In the physical group, the decline was more pronounced than in the mental group even with significance ($p < 0.01$).



(a) *PAT* (ms) (b) *HR* (1/min)

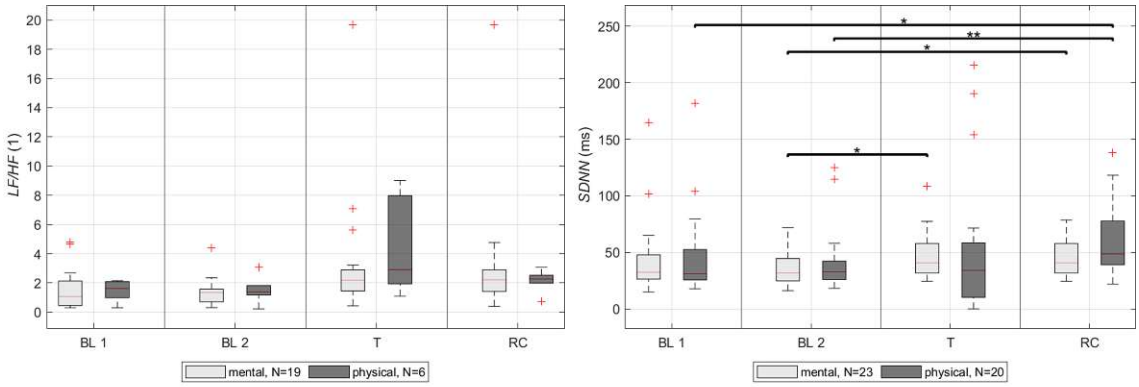
Figure 4.9: Grouped boxplots of *PAT*s (ms) and *HR*s (1/min) during both baselines (BL1, BL2), the task (T) and at the end (RC) for mental and physical tasks. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

Heart rates from mental and physical groups are shown in figure 4.9b. Similar to *PAT*, there was a significant difference in *HR*s during the task phase, with the *HR* in the physical group exceeding that of the mental group ($p < 0.001$). This trend could also be seen in the recovery phase, but without significance. In the baselines the groups behaved the same. Considering the individual groups separately, *HR* during the mental task increased mid-significantly ($p < 0.01$) to both baselines and was slightly significantly higher ($p < 0.05$) at the end than the baseline value. In the physical group, however, highly significant differences ($p < 0.001$) occurred during the task compared to all other phases, meaning that *PAT* during the task exceeded all other phases. *HR* during the recovery phase was also statistically significantly greater than both baseline values (BL1 $p < 0.01$, BL2 $p < 0.001$). Heart rates of both groups increased between the beginning and end of the recording, the physical task group reached significance ($p < 0.01$), whereas the mental task group increased only slightly without significance. They are slightly significantly different ($p < 0.05$).

4.2.3 Heart Rate Variability

LF/HF power ratios, *SDNN*s and *RMSSD*s, allocated according to the type of task, were not normally distributed, thus, their medians with first and third quartiles were calculated and are listed in the table 4.4.

LF/HF power ratios for the mental and physical group are illustrated in figure 4.10a as boxplots. No statistically significant differences could be identified between the mental and physical group in the *LF/HF* values. Subjects who had completed the physical task generally had higher *LF/HF* values, but the amount of usable data was very small for the physical task, thus, clear conclusion could not be drawn. From the first and second baseline to the task, *LF/HF* values increased in both groups. However, in the physical group, *LF/HF* values decreased again after the task but after the mental task, the values stayed elevated. The initial values were not reached again at the end in both groups. *LF/HF* changes of both group between beginning and end were slightly different, *LF/HF* increased, but without significance.



(a) *LF/HF* (1) (b) *SDNN* (ms)

Figure 4.10: Grouped boxplots of *LF/HF*s (1) and *SDNN*s (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) for mental and physical tasks. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

*SDNN*s of the both groups are shown in figure 4.10b. A comparison of the *SDNN* values of the physical and mental group also showed no statistically significant differences. During the physical task, *SDNN* decreased more than during the mental task. In addition, in the recovery phase after the physical task, *SDNN* also increased more than during the recovery from the mental task. When examining the *SDNN* values per groups separately, there were statistically significant differences. *SDNN*s during the mental task increased slightly significantly ($p < 0.05$) compared to the second baseline, as did the recovery phase compared to the second baseline. Meanwhile, after the physical task in the recovery phase, the *SDNN* increased slightly significantly ($p < 0.05$) compared to the first baseline and signficantly ($p < 0.01$) compared to the second baseline. *SDNN* change between the between beginning and end of the measurement of the mental group was not significantly different, however,

a small increase was noticeable. The change of the physical group stood out significantly ($p < 0.05$) from the mental group, its difference was significantly higher ($p < 0.01$) towards the end of the experiment.

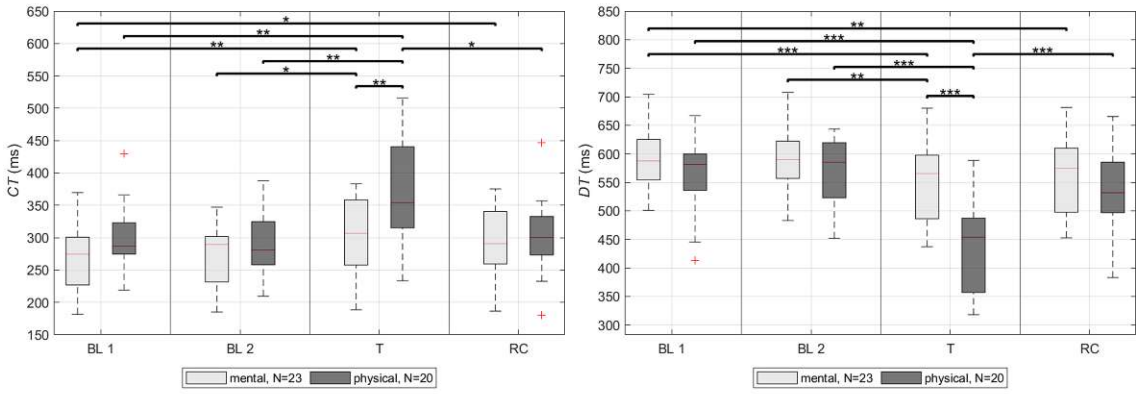
*RMSSD*s of the mental and physical groups are shown in the Appendix A.2.1 in figure A.1a. Similar to the *LF/HF*, there were no statistically significant differences in the *RMSSD* values between the groups. After the mental task, the *RMSSD* values increased slightly, whereas after the physical task they tended to remain the same. Here, only the variance increased. The initial values could not be reached again at the end, a slight increase could be noted. Final values of the physical group rose more compared to the beginning than the final values of the mental group, however, without significance.

4.2.4 Pulse Wave Characteristics

Crest times, durations of diastole and notch times, which were split by the task, were normally distributed, so their mean values and standard deviations were calculated and are shown in the table 4.4.

The corresponding boxplots for the crest times of the different groups are shown in figure 4.11a. *CT*s during the mental and physical task showed a significant difference ($p < 0.01$). During the physical task, CT rose more than during the mental one. When looking at them separately, CT at the mental and physical task increased significantly ($p < 0.01$) compared to their first baseline, as well as significantly (mental task group $p < 0.05$, physical group $p < 0.01$) to their second baseline. However, CT dropped significantly ($p < 0.05$) after the physical task and only slightly after the mental task. Overall, there was an increase in both groups between the beginning and the end of the recording. In the mental group, the difference was significantly different ($p < 0.01$), it showed an increase, while in the physical group, only a minimal increase was seen without significance.

The durations of the diastole in both groups are shown in figure 4.11b. There was also a significant difference between the mental and physical task in the duration of the diastole. The physical task caused the DT to drop highly significantly more ($p < 0.001$) than the mental task. After the task, the physical group remained also below the mental group. Although not clearly visible, the DT dropped significantly during the mental task compared to both previous baseline periods (BL1 $p < 0.001$, BL2 $p < 0.01$), afterwards it stayed on the task level. During the physical task, the DT decreased highly significantly ($p < 0.001$) compared to all other phases. Overall, DT decreased in both groups between the beginning and the end of the recording. In the mental group, the difference between beginning and end was highly significant ($p < 0.001$), while only a minimal decrease was seen in the physical group.



(a) CT (ms) (b) DT (ms)

Figure 4.11: Grouped boxplots of CTs (ms) and DTs (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) for mental and physical tasks. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

Notch times showed the same trend as crest times in the mental and physical group, even the level of significance were the same. Comparing final values with the beginning, NTs of both groups increased, however, only the difference of the mental group differed highly significantly ($p < 0.001$). The corresponding figure is shown in Appendix A.2.2 in figure A.2a.

The IPAs, which were allocated to the type of task, were normally distributed, so means and standard deviations were calculated and are listed in the table 4.4.

Figure 4.12 shows the grouped boxplot of IPAs between the mental and physical group. There were significant differences between the IPAs of the mental and physical group during the task phase where IPA dropped significantly ($p < 0.001$) more during the physical task than during the mental one. In the recovery phase this trend prevailed, but without significance. Looking at the different groups separately exhibited following statistically significant differences. IPA of the mental participants decreased significantly from both baselines to the task (BL1 $p < 0.01$, BL2 $p < 0.001$) and stayed at the task level during the recovery. The same decreasing trend could be seen in the participants who performed the pyhsical task, thus, IPA decreased in the task period significantly ($p < 0.01$) but it afterwards increased again significantly ($p < 0.01$). Final IPA values of both groups deviated significantly from the initial values, they decreased during the course of the experiment (mental $p < 0.01$, physical $p < 0.001$).

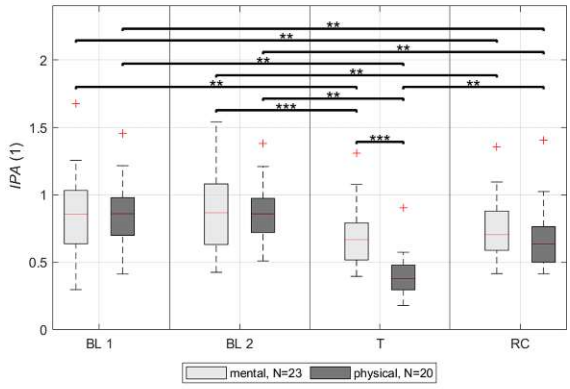


Figure 4.12: Boxplots of the averaged *IPA*s (1) at both baselines (BL1, BL2), during the task (T) and at the end (RC) for mental and physical tasks. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.3 Sex

The subjects population was also divided into their sex, either male or female. Apart from any differences between the groups, it was also checked whether there was a decrease or increase in the groups between the beginning and end of the measurement that was statistically different from zero. Not all parameters will be described here, only those that exhibited a statistically significant or an interesting progression and the remaining plots are shown in Appendix A.2.
All in all, 48 subjects measurement sets could be used, comprising 28 male participants and 20 female participants. A more detailed breakdown of the 48 participants is shown in table 4.5.

Table 4.5: Breakdown of the participants according to the sex and further breakdown into the nature of the task, age and blood pressure classes.

	$\sum$	**mental**	**physical**	**younger** age < 64.6 years	**older** age > 64.6 years	**BP normal**	**BP elevated**	**BP grade 1**
male	28	17	11	11	17	11	9	8
female	20	9	11	11	9	10	3	7

All useful, and further described parameters and the number of used measurement sets for the male participants and female participants are listed in the table 4.6. Data belonging to a normal distribution are represented with means and standard deviations (mean (SD)) and non-normally distributed data are represented with medians and interquartile ranges (median [IQR]).

Table 4.6: Means with standard deviations in round brackets, medians with interquartile ranges in square brackets and number of used measurement sets of the different parameters during both baselines, the task and the recovery for the female and male participants.

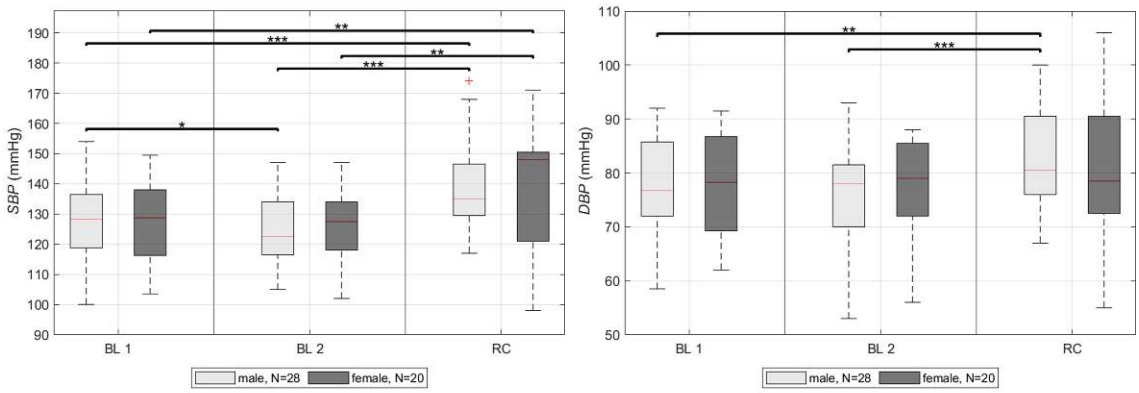
		Baseline 1	Baseline 2	Task	Recovery	N (#)
SBP (mmHg)	male	128.11 (12.50)	124.41 (11.17)	-	138.48 (14.82)	28
	female	127.70 (13.25)	125.55 (12.50)	-	139.70 (20.89)	20
DBP (mmHg)	male	77.74 (8.96)	75.93 (8.60)	-	82.00 (9.04)	28
	female	77.67 (9.49)	77.15 (9.15)	-	80.90 (14.15)	20
PAT (ms)	male	273.59 (34.87)	264.48 (31.48)	254.46 (33.82)	263.28 (33.25)	21
	female	248.10 (31.66)	246.75 (30.41)	212.01 (45.81)	228.25 (34.70)	16
HR (1/min)	male	70.20 (13.14)	69.61 (12.72)	84.04 (20.88)	72.82 (13.14)	25
	female	73.28 (10.81)	72.29 (11.00)	96.76 (20.02)	78.73 (12.66)	20
LF/HF (1)	male	1.23 [0.48, 2.12]	1.41 [0.64, 1.57]	2.35 [1.51, 3.35]	2.33 [1.51, 3.02]	16
	female	1.32 [0.83 , 2.11]	1.27 [1.15, 1.83]	2.20 [1.73, 3.77]	2.02 [1.30, 2.59]	9
SDNN (ms)	male	29.63 [25.18, 44.22]	28.74 [23.54, 39.18]	36.32 [29.51, 59.22]	39.69 [32.62, 59.09]	24
	female	34.32 [29.44, 56.98]	37.40 [30.90, 49.88]	40.72 [24.36, 50.13]	48.95 [39.43, 74.15]	19
RMSSD (ms)	male	31.82 [25.08, 41.62]	32.00 [26.32, 44.57]	29.93 [25.87, 43.22]	29.06 [26.98, 43.12]	21
	female	30.29 [25.61, 47.49]	31.04 [28.24, 40.63]	31.59 [26.52, 53.56]	36.27 [30.37, 42.37]	16
CT (ms)	male	271.96 (60.58)	271.85 (53.87)	318.02 (86.37)	286.70 (65.45)	25
	female	297.05 (30.59)	294.97 (35.38)	351.60 (63.16)	307.17 (37.35)	18
DT (ms)	male	585.76 (72.09)	585.20 (62.22)	514.32 (106.15)	562.36 (75.75)	25
	female	571.20 (37.89)	569.24 (50.39)	470.38 (71.62)	536.74 (58.64)	18
NT (ms)	male	414.24 (72.09)	414.80 (62.22)	485.68 (106.15)	437.64 (75.75)	25
	female	428.80 (37.89)	430.76 (50.39)	529.62 (71.62)	463.26 (58.64)	18
IPA (1)	male	0.87 (0.31)	0.89 (0.28)	0.60 (0.27)	0.75 (0.26)	25
	female	0.85 (0.18)	0.85 (0.19)	0.49 (0.18)	0.67 (0.19)	18

4.3.1 Blood Pressure

Blood pressure data were divided according to the sex. Systolic and diastolic blood pressures were normally distributed, so mean values and standard deviations were calculated and are listed in the table 4.6.

Grouped boxplots for the systolic blood pressure of the male and female subjects are shown in figure 4.13a. No significant differences between the male and female *SBP*s were found. However, if looking at the groups separately, there were significant differences in the *SBP* between the phases. In the male group, a highly significant increase ($p < 0.001$) in the recovery phase compared to the baseline periods could be observed. Here again, a slightly significant decrease ($p < 0.05$) could be observed between the first and second baseline, whereas in the female group, this differences did not occur. Despite, the *SBP* in the recovery phase of the female group stood out in a significant way ($p < 0.01$) from the two baseline periods as well. Overall, there was a significant increase in *SBP* in the male ($p < 0.001$)

and female group ($p < 0.01$) between the beginning and the end of the experiment. The value of the female group increased more.



(a) *SBP* (mmHg) (b) *DBP* (mmHg)

Figure 4.13: Grouped boxplots of blood pressures (mmHg) during both baselines (BL1, BL2) and at the end (RC) for male and female groups. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

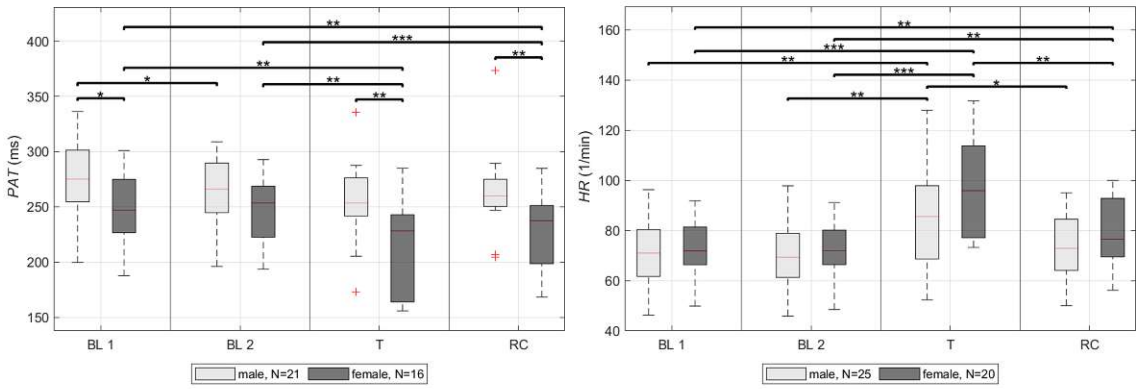
Figure 4.13b shows the diastolic blood pressure of the male and female group. As with the *SBP*, there were no significant differences in the *DBP* between the male and female groups. Considering the *DBP* separately, only in the male group significant differences were existent. Here, the recovery phase increased significantly to both baselines (BL1 $p < 0.01$, BL2 $p < 0.001$). In the female group, the median and quartile range remained quite the same, as visualized in the boxplot. The *DBP* at the beginning and end significantly differed ($p < 0.01$) from another in the male group, meanwhile *DBP* in the female group differed as well but without significance. Both groups increased towards the end of the experiment.

4.3.2 Pulse Arrival Time and Heart Rate

Pulse arrival times and heart rates allocated to the sex were all normally distributed, hence, mean values and standard deviations were calculated and are listed in the table 4.6.

In comparison to blood pressure, significant differences between the sexes occurred in the *PAT*, as seen in figure 4.14a. *PAT* dropped more in the female group than in the male group during the task and during the recovery ($p < 0.01$). This trend was also seen in both baselines, however, statistical significance were only reached in the first baseline ($p < 0.05$). Considering the groups separately, *PAT* of the male group decreased with the task and increased slightly afterwards but could not reach significance and could not reach the initial value, however, the second baseline decreased slightly significantly ($p < 0.05$) compared to the first baseline. This could only be seen in the male group. In the female group however, *PAT* during the task was significantly reduced ($p < 0.01$) compared to the baseline periods. The same occurred in the recovery phase, where *PAT* was significantly reduced compared to the baseline periods (BL1 $p < 0.01$, BL2 $p < 0.001$) but slightly

increased after the task. Overall, *PAT*s of both groups dropped between the beginning and the end of the measurement. The *PAT* between beginning and end of the recording of the group of male participants differed slightly significantly ($p < 0.05$), while changes in the female participants differed highly significantly ($p < 0.001$) and fell even more than the values of the male group.



(a) *PAT* (ms)

(b) *HR* (1/min)

Figure 4.14: Grouped boxplots of *PAT*s (ms) and *HR*s (1/min) during both baselines (BL1, BL2), the task (T) and at the end (RC) for male and female groups. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

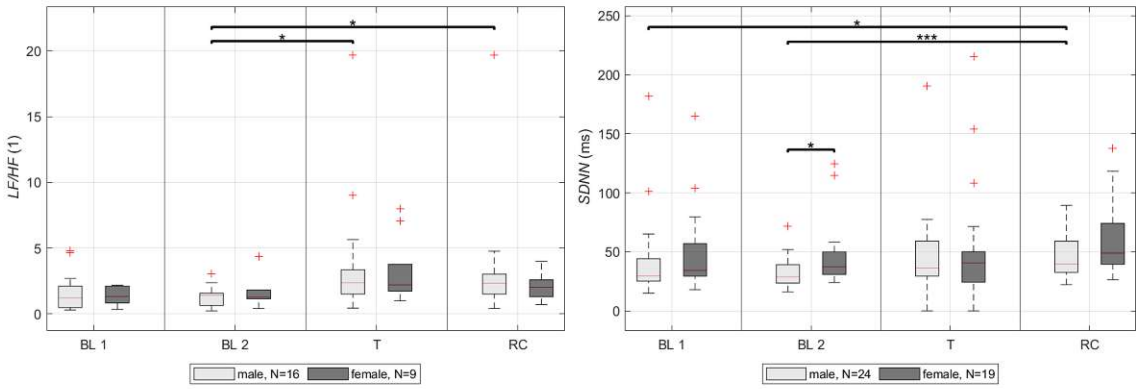
Figure 4.14b illustrates the grouped boxplot of *HR*s in the male and female group. There were no significant differences in the *HR* between the groups, although *HR*s of the female participants increased in the task and recovery phase more than in men. When examining the group separately, the following could be seen. The *HR* of men during the task was statistically significantly elevated ($p < 0.01$) from the baseline phases and decreased ($p < 0.05$) again in the recovery phase. For the women, the *HR* during the task phase was also statistically significantly elevated from the baseline periods ($p < 0.001$) and decreased significantly afterwards ($p < 0.01$) but stayed slightly elevated. Overall, final values differed significantly from the initial values of both groups. The group of male participants showed a slightly significant increase ($p < 0.05$) and the group of female participants showed as well an increase ($p < 0.01$). The two groups were slightly significantly different ($p < 0.05$) in their trends.

4.3.3 Heart Rate Variability

LF/HF power ratios, *SDNN*s and *RMSSD*s were split by their sex and as their values were not normally distributed, their medians, first and third quartiles were calculated and are listed in the table 4.6.

*LF/HF*s of the male and female participants are shown as grouped boxplots in figure 4.15a. During the task and the recovery phase, *LF/HF* values of men seemed to be higher than *LF/HF* values of women. Considering the men separately, *LF/HF* increased significantly

with the task ($p < 0.05$) and also during the recovery phase ($p < 0.05$) compared to the second baseline. In the end, the baseline value could not be reached. For women, on the other hand, *LF/HF* increased during the task and fell afterwards again, however, without significance. Here, the initial value seemed to be almost reached again. Overall, the final values differed from the initial values for both groups, they slighty increased towards the end but without significance.



(a) *LF/HF* (1)

(b) *SDNN* (ms)

Figure 4.15: Grouped boxplots of *LF/HF*s (1) and *SDNN*s (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) for male and female groups. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

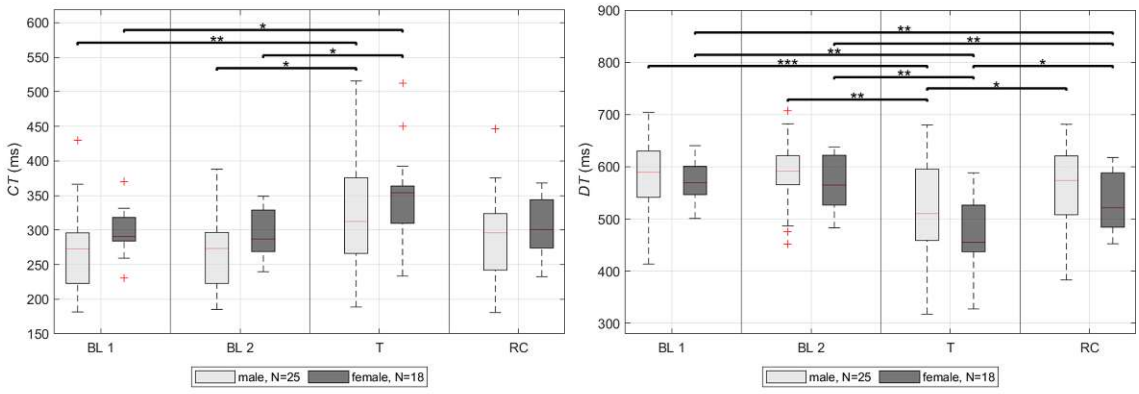
Figure 4.15b illustrates *SDNN*s for the male and female group as grouped boxplots. Statistically significant differences occurred during the second baseline between the sexes, such that *SDNN* of the male showed a slightly significant ($p < 0.05$) decrease. Overall, it seemed that *SDNN*s of women were higher than those of men in the baseline periods and in the recovery phase, only in the task phase *SDNN* of women decreased more. *SDNN* in the recovery phase of the male group increased significantly compared to both baselines (BL1 $p < 0.05$, BL2 $p < 0.001$). In the female group, *SDNN*s increased with the task and in the recovery phase, but without significance. The initial value could not be reached again at the end. Overall, *SDNN* values of both groups increased between the beginning and the end of the measurement. The difference of *SDNN* between beginning and end of the male group was significant ($p < 0.01$), while the difference of *SDNN* of the female group was without significance.

*RMSSD*s exhibited no differences between the two groups. Considered separately, there were no significant differences either, only *RMSSD* of the women increased more in the recovery phase after the task than in men, but without significance. Apart from that, *RMSSD* remained on the same level. Over the course of the study, *RMSSD* of both groups increased, but without significance. The boxplot for *RMSSD*s of the male and female group is shown in the Appendix A.2.1 in figure A.1b.

4.3.4 Pulse Wave Characteristics

Crest times, durations of diastole and notch times were split by sex. As they were normally distributed, their means and standard deviations were calculated and are shown in the table 4.6.

Figure 4.16a illustrates CTs of the male and female participants as boxplots. As it can be seen, there were also no statistically significant differences between the two groups. The values of the female group seemed to be higher than the ones of the male group throughout the study. Considered separately, CT during the task was significantly increased compared to the both baselines in the male (BL1 $p < 0.01$, BL2 $p < 0.05$) as well in the female group (BL1 and BL2 $p < 0.05$). After the task, they fell again and almost reached the initial state again. Overall, CTs increased in both groups between the beginning and end of the recordings. CT changes of the male group stood out more than the female group changes, however, both without significance.



(a) CT (ms) (b) DT (ms)

Figure 4.16: Grouped boxplots of CTs (ms) and DTs (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) for male and female groups. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

DTs for the male and female participants are shown in figure 4.16b as boxplots. As with CT, there were no statistically significant differences between the male and female groups. In general, the female group had lower DT values than the male group. Considered in the individual groups, there were significant differences. In the male group, DTs dropped significantly in the task phase compared to the baseline values (BL1 $p < 0.001$, BL2 $p < 0.01$). After the task, DT values increased slightly significantly ($p < 0.05$) again and the initial value seemed to be almost reached. In the female group, DT during the task phase also decreased significantly ($p < 0.01$) compared to the initial values, and also here the DT increased slightly significantly ($p < 0.05$) after the task. The final DT value for the female group rose significantly compared to both baselines. There was a decrease in DT in both groups between the start and end of the experiment. Both groups differed significantly in their beginning to end values. DT of the male group changed slightly significantly

($p < 0.05$) between beginning and end, while DT of the female group changed highly significantly ($p < 0.001$).

NTs demonstrated a similar behavior. The boxplots for NTs of the male and female participants are shown in the Appendix A.2.2 in figure A.2b. In the group of men, NT increased significantly in the task (BL1 $p < 0.001$, BL2 $p < 0.01$) and decreased slightly significant ($p < 0.05$) again in the recovery phase. The same pattern could be observed in the female group, where the NT during the task increased significantly ($p < 0.01$) compared to both baselines and decreased slightly significant ($p < 0.05$) again. However, the recovery value significantly rose ($p < 0.01$) in relation to the first and second baseline in the female participants, which was not the case in the male group. For both groups, NT scores increased overall between the beginning and end of the recordings. NT of the male group was slightly significantly different ($p < 0.05$), whereas NT of the female group was strongly significantly different ($p < 0.001$) between the beginning and end.

Inflection point areas were divided by their sex and as they were normally distributed, their means with standard deviations were calculated and are listed in the table 4.6.

The corresponding boxplots of IPA for male and female participants can be seen in Figure 4.17. No significant differences were found between the groups, but significant differences were found between the phases of each group. Across the board, IPAs of the female participants showed smaller scores than those of the male participants. During the task phase, IPAs of both groups decreased significantly, IPAs of men decreased highly significantly ($p < 0.001$) and IPAs of women decreased mid significantly ($p < 0.01$), however, they decreased more. In the recovery phase, IPA of male participants increased slightly significantly ($p < 0.05$) again, while IPA of the female participants only rose slightly and without significance. The IPAs of the male and female groups decreased significantly between the beginning and the end of the recording (male group $p < 0.01$, female group $p < 0.001$). IPAs of the female participants decreased visibly more, but without significant difference to the value of the male participants.

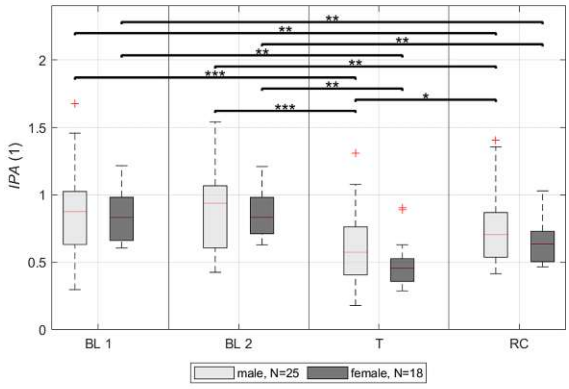


Figure 4.17: Boxplots of the averaged *IPA*s (1) values at both baselines (RC), during the task (T) and at the end (RC) for male and female groups. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.4 Age

After the grouping by mental and physical task and by gender, the grouping by age was carried out. The mean age of all participants was 64.6 years, thus participants who were older or younger than the mean age were allocated to the corresponding older or younger group. As already mentioned above, not only the difference between the groups was taken into account, but also whether an increase or decrease of the values between the beginning and the end of the experiment could be seen. In addition, not all parameters were described. The 48 useful measurement sets were broken down to their age, whether they were older or younger than the average. A more detailed breakdown of the participants can be seen in table 4.7.

Table 4.7: Breakdown of the participants into their age (younger or older than the average) and further breakdown into the nature of the task, sex and blood pressure classes.

	$\sum$	**mental**	**physical**	**male**	**female**	**BP normal**	**BP elevated**	**BP grade 1**
older age < 64.6 years	26	15	11	17	9	10	7	9
younger age > 64.6 years	22	11	11	11	11	17	5	6

All useful and further described parameters with the number of used measurement sets for the group with participants older than the average and for the group with participants younger than the average, are listed in the table 4.8. Data belonging to a normal distribution are represented with means and standard deviations (mean (SD)) and non-normally distributed data are represented with medians and interquartile ranges (median [IQR]).

Table 4.8: Means with standard deviations in round brackets, medians with interquartile ranges in square brackets and number of used measurement sets of the different parameters during both baselines, the task and the recovery for the younger and older than the mean age of 64.6 years group.

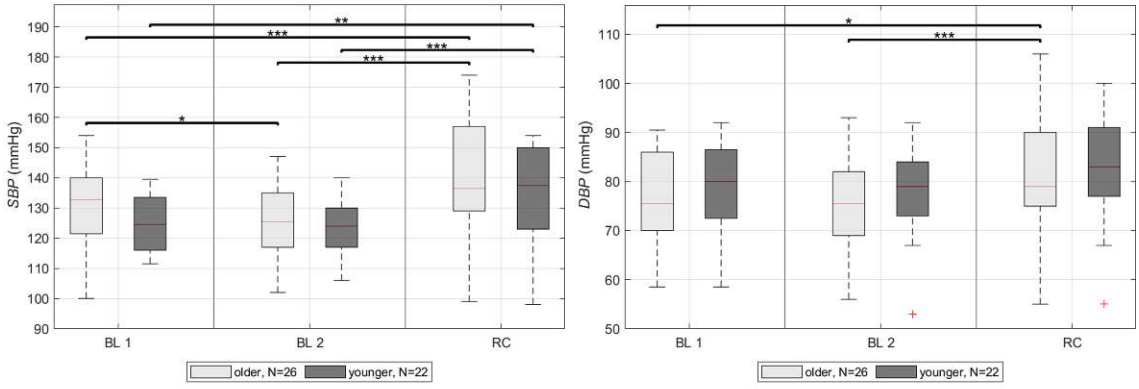
		Baseline 1	Baseline 2	Task	Recovery	N (#)
SBP (mmHg)	older	130.35 (14.30)	126.50 (12.94)	-	141.23 (19.07)	26
	younger	124.95 (9.86)	122.91 (9.73)	-	136.24 (15.22)	22
DBP (mmHg)	older	77.10 (9.44)	75.35 (8.86)	-	81.58 (12.01)	26
	younger	78.48 (8.80)	77.81 (8.66)	-	81.48 (10.82)	22
PAT (ms)	older	255.78 (2.54)	248.29 (36.01)	232.63 (38.69)	240.20 (35.13)	18
	younger	268.99 (26.75)	264.89 (25.77)	239.39 (49.92)	255.65 (39.54)	19
HR (1/min)	older	72.82 (12.78)	71.78 (12.15)	87.98 (19.41)	77.07 (14.84)	23
	younger	70.27 (11.55)	69.78 (11.88)	91.49 (23.34)	73.59 (11.15)	20
LF/HF (1)	older	0.99 [0.53, 1.70]	1.27 [0.83, 1.64]	1.74 [1.18, 2.64]	1.61 [0.88, 2.51]	11
	younger	2.01 [0.36, 2.16]	1.45 [0.74, 1.59]	2.35 [2.08, 3.48]	2.55 [1.99, 3.07]	14
SDNN (ms)	older	30.73 [23.87, 52.31]	31.24 [24.50, 40.55]	40.72 [26.88, 63.07]	40.72 [31.97, 60.22]	21
	younger	34.38 [27.82, 48.41]	36.19 [28.19, 42.58]	36.32 [24.39, 55.75]	47.75 [38.53, 73.90]	22
RMSSD (ms)	older	28.55 [25.62, 41.62]	31.59 [27.16, 46.29]	30.45 [27.45, 51.62]	37.95 [29.53, 43.60]	17
	younger	32.34 [24.84, 43.98]	31.56 [27.37, 40.68]	29.76 [25.50, 37.96]	29.20 [26.16, 39.80]	20
CT (ms)	older	295.93 (53.50)	290.49 (43.72)	330.33 (67.71)	315.00 (52.00)	26
	younger	261.86 (41.15)	267.81 (52.11)	334.74 (94.81)	265.09 (48.53)	17
DT (ms)	older	564.01 (64.85)	569.96 (59.48)	499.40 (90.68)	529.26 (71.00)	26
	younger	603.61 (43.38)	591.61 (53.31)	490.62 (103.53)	585.86 (52.49)	17
NT (ms)	older	435.99 (64.85)	430.04 (59.48)	500.60 (90.68)	470.74 (71.00)	26
	younger	396.39 (43.38)	408.39 (53.31)	509.38 (103.53)	413.14 (52.49)	17
IPA (1)	older	0.81 (0.24)	0.85 (0.23)	0.58 (0.22)	0.67 (0.20)	26
	younger	0.94 (0.28)	0.91 (0.27)	0.52 (0.27)	0.78 (0.27)	17

4.4.1 Blood Pressure

Systolic and diastolic blood pressure were allocated to the older and younger group. Since they were normally distributed, their mean values and standard deviations were calculated and are listed in the table 4.8.

Systolic blood pressure of the groups older and younger than the mean age are illustrated in figure 4.18a. There were no significant differences between the groups. The group of younger participants consistently showed a slightly lower *SBP* value than participants of the older group. Looking at the groups separately, a highly significant increase ($p < 0.001$) in *SBP* in the recovery phase compared to the two previous baseline phases in the older group, as well as in the younger group (BL1 $p < 0.01$, BL2 $p < 0.001$) was observed. In addition, in the older group, there was a statistically significant decrease ($p < 0.05$) in *SBP* between the first and second baseline period. This could only be observed in the older group. Overall, both groups showed an increase in *SBP* values between the beginning and

end of the experiment. The differences were highly significant ($p < 0.001$) in both groups.



(a) *SBP* (mmHg)

(b) *DBP* (mmHg)

Figure 4.18: Grouped boxplots of blood pressures (mmHg) during both baselines (BL1, BL2) and at the end (RC) allocated to the groups of participants younger and older than the mean age. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

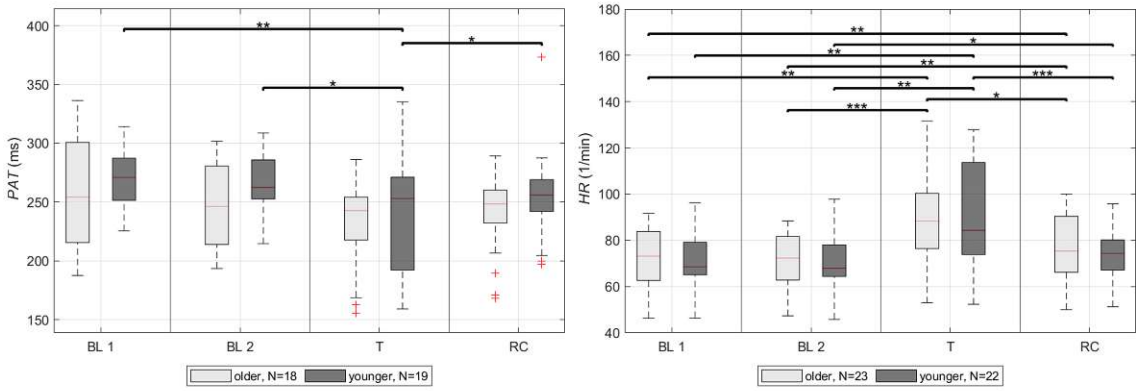
Figure 4.18b shows the diastolic blood pressure for the older and younger group. As with the *SBP*, no significant differences could be detected between the groups. The younger participants consistently showed higher *DBP* values than the older ones. When looking at the individual groups, there were only significant differences in the older group. Here, the values during the recovery phase were statistically significantly different from the two previous baseline periods (BL1 $p < 0.05$, BL2 $p < 0.001$). In the group of younger participants, the increase in *DBP* in the recovery phase could be recognised despite the lack of significance. *DBP* increased in both groups between the beginning and end of the experiment. The difference between the start and end of the older participants was slightly significant ($p < 0.05$), while the values of the younger participants were only minimally different.

4.4.2 Pulse Arrival Time and Heart Rate

Pulse arrival times and heart rates were evaluated in the groups older or younger than the mean age. Their values were normally distributed, thus their means and standard deviations were calculated and are listed in the table 4.8.

The boxplots of the *PAT*s for younger and older participants are shown in figure 4.19a. No significant differences could be found between the two groups. During the task, the values of both groups dropped slightly and rose again briefly in the recovery phase. *PAT*s of the younger participants showed slightly higher values than *PAT*s of the older participants throughout the study. In the group of older participants, there were no statistically significant differences between the phases, nonetheless the decrease during the task and the slight increase during recovery could be recognised. In the younger participants, on the other hand, *PAT* decreased statistically significantly during the task (BL1 $p < 0.01$,

BL2 $p < 0.05$) and increased afterwards again ($p < 0.05$). Overall, there was a reduction in *PAT* values between the beginning and the end of the measurement. Both groups *PAT* values deviated significantly ($p < 0.01$) between the beginning and end, those of the older ones decreased slightly more over the measurements than those of the younger ones.



(a) *PAT* (ms) (b) *HR* (1/min)

Figure 4.19: Grouped boxplots of *PAT*s (ms) and *HR*s (1/min) during both baselines (BL1, BL2), the task (T) and at the end (RC) allocated to the groups of participants younger and older than the mean age. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

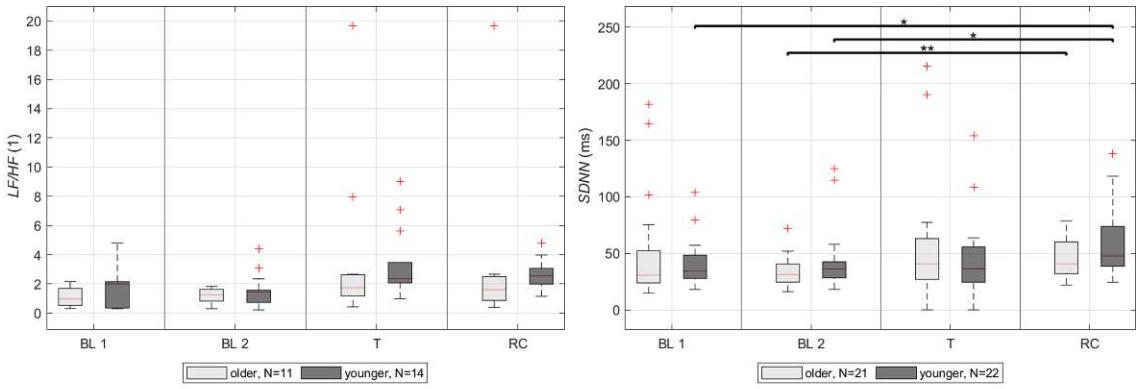
Heart rates of the younger and older groups are shown in figure 4.19b as grouped boxplots. As with *PAT*, no significant differences between the groups could be found in the *HR*. During the baseline periods and the recovery it seemed, as if the older group had a higher heart rate. When looking at the individual groups, there were significant differences between the phases. In the older participants, *HR* during the task increased significantly (BL1 $p < 0.01$, BL2 $p < 0.001$) and slightly decreased afterwards ($p < 0.05$). Recovery *HR* values also differed significantly ($p < 0.01$) from the two baseline periods. In the younger participants, however, only the task phase increased significantly ($p < 0.01$) in relation to the baseline periods and decreased highly significantly ($p < 0.001$) afterwards, but the recovery phase was not significantly different from the baseline periods. Overall, HRs between the beginning and the end of the recordings of the older participants showed a significant increase ($p < 0.01$), meanwhile the younger participants showed only a slightly significant increase ($p < 0.05$).

4.4.3 Heart Rate Variability

LF/HF power ratios, *SDNN*s and *RMSSD*s were evaluated in groups older or younger than the mean age. Since the values were not normally distributed, their medians with first and third quartiles were calculated and are listed in the table 4.8.

Figure 4.20a depicts the *LF/HF*s of the older and younger participants. Likewise, no significant differences could be found between the two groups. Since the number of usable

data was quite small here, the following comments should be treated with caution. It seemed as if *LF/HF*s of the younger group were higher than those of the older group during the task and later in the recovery phase. However, both groups showed an increase during the task and stayed elevated afterwards. Overall, *LF/HF* values increased slightly from the beginning to the end of the measurements in both groups, but without significance.



(a) *LF/HF* (1)

(b) *SDNN* (ms)

Figure 4.20: Grouped boxplots of *LF/HF*s (1) and *SDNN*s (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) allocated to the groups of participants of younger and older than the mean age. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

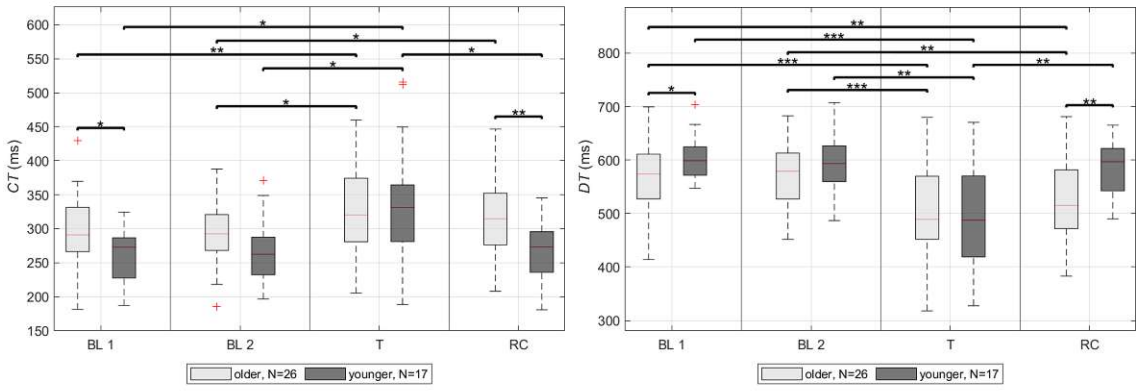
*SDNN*s from the older and younger participants are presented in the figure 4.20b as grouped boxplots. The *SDNN* values did not show any significant differences between the groups either. It seemed as if the *SDNN*s of the older participants were higher than those of the younger ones during the task, but during the recovery phase it looked the other way round. There were significant differences between the phases within the groups. In both groups the recovery values were significantly higher than each second baseline value (older group $p < 0.01$, younger group $p < 0.05$). In addition, the younger participants showed also a slightly significant increase ($p < 0.05$) between the first baseline and the recovery. During the task phase, it seemed that *SDNN* increased in the older group already and in the younger group only after the task. Overall, there was a slight increase in *SDNN* values from the beginning to the end of the recording. The difference from the beginning to the end of the group of younger participants was significant ($p < 0.01$), while the group of older participants was without significance.

RMSSD values also showed no significant differences between the groups. Participants older than the mean age showed significantly elevated *RMSSD* values during the recovery phase compared to the first baseline phase, while participants of the younger group showed no differences. This could also be seen in the differences between the beginning and the end. Towards the end, *RMSSD* of the older group increased significantly ($p < 0.05$) and *RMSSD* of the younger group did not change. The corresponding figure is shown in the Appendix A.2.1 in figure A.1c.

4.4.4 Pulse Wave Characteristics

Crest times, durations of diastole and notch times were split into the groups older or younger participants. Since they were normally distributed, their means and standard deviations were calculated and are listed in the table 4.8.

Crest times of the older and younger group are shown in figure 4.21a. One can clearly see that CT of the older participants were higher in the baseline phases and in the recovery phase than those of the younger ones. In the first baseline this difference reached a slight significance ($p < 0.05$) and in the recovery phase the level of significance increased ($p < 0.01$). During the task CTs of both groups were significantly higher than during the baseline periods (either $p < 0.05$ or $p < 0.01$). For the older participants, the CT value dropped only slightly after the task, while for the younger participants it dropped sharply and showed a significant change ($p < 0.05$) towards the task phase. This could also be seen in the differences between the initial values and the final values. The group of older participants stood out significantly ($p < 0.05$) with their final value from the initial value, they were elevated. On the other hand, CT of the younger participants almost returned to the initial value.



(a) CT (ms) (b) DT (ms)

Figure 4.21: Grouped boxplots of CTs (ms) and DTs (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) allocated to the groups of participants of younger and older than the mean age. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

Figure 4.21b represents the DTs of younger and older participants as boxplots. DTs of the older participants in the baseline periods and the recovery phase were lower than those of the younger ones, this observation reached in the first baseline ($p < 0.05$) and recovery phase ($p < 0.01$) statistical significance. In the individual groups, there was a significant drop in DT during the task; older participants decreased highly significantly ($p < 0.001$) to both baselines, younger participants decreased highly significantly ($p < 0.001$) to the first and mid significantly to the second baseline. In the older participants, DT increased slightly after the task and remained statistically significantly ($p < 0.01$) below the initial

value, while the DT of the younger participants increased significantly ($p < 0.01$) again in the recovery period. Overall, DT scores of both groups decreased between the beginning and the end of the measurement. The change of the group of older participants stood out significantly ($p < 0.001$) and the change of the group of younger participants stood out slightly but without significance.

The notch time behaved similarly to the crest time. NTs of the younger participants were again lower throughout the baseline and recovery phases, meanwhile NTs of both groups remained on the same level during the task. The same statistically significant differences between the groups were evident here as they were evident in the DTs. During the task NTs of older and younger participants rose highly significantly ($p < 0.001$) from their baseline phases, only NT of the younger group rose from the second baseline with a reduced level of significance ($p < 0.01$). Similar to DT, only the younger participants showed a significant decrease ($p < 0.01$) after the task in the recovery phase. NTs of the older participants increased significantly ($p < 0.01$) in the recovery phase compared to both baseline phases, while NTs of the younger participants reached their initial values again. Taken as a whole, NTs of the older group increased highly significantly ($p < 0.001$) between beginning and end of the recording, the younger group showed nearly no change. The boxplots are shown in the Appendix A.2.2 in figure A.2c.

Inflection point areas for the older and younger participants were normally distributed, thus their mean values and standard deviations were calculated and are listed in the table 4.8.

Boxplots of the IPAs for the younger and older participants are shown in Figure 4.22. There were no significant differences between the groups but differences between the phases of the experiment per group. The values in the group of younger participants had the highest IPA score in the first baseline period, meanwhile in the second baseline phase the two groups were approximately equal. With the task, values of both groups decreased significantly (older group $p < 0.001$, younger group $p < 0.01$), the older participants decreased with their IPA more, but not significantly different. After the task phase, IPAs of the group of younger participants increased significantly ($p < 0.01$) again. In contrast, IPAs of the group of older participants increased only slightly, but without significance. Overall, the IPAs of both groups decreased highly significantly ($p < 0.001$) between the beginning and the end of the experiment.

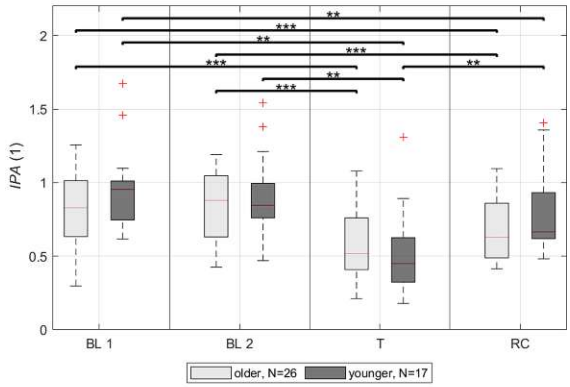


Figure 4.22: Boxplots of the averaged *IPA*s (1) at both baselines (BL1, BL2), during the task (T) and at the end (RC) allocated to groups of participants younger and older than the mean age. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

4.5 Blood Pressure Grade

As a final classification, the participants were divided according to their blood pressure class. As with the other classifications, the differences between the groups and differences between initial and final values were examined, but not all parameters were described here. All 48 measurement sets were broken down to their blood pressure classes, either normal, elevated blood pressure or hypertension grade 1, since no one of the 48 remaining participants was diagnosed with hypertension grade 2. The number of participants who performed the mental or physical task, who were male or female and whether they were younger or older than the average, is listed in the following table 4.9.

Table 4.9: Breakdown of the participants into their blood pressure classes (normal BP, elevated BP and hypertension grade 1) and further breakdown into the nature of the task, sex and age.

	$\sum$	**mental**	**physical**	**male**	**female**	**older** age $<$ 64.6 years	**younger** age $>$ 64.6 years
BP normal	21	11	10	11	10	10	11
BP elevated	12	9	3	6	6	7	5
BP Hypertension grade 1	15	8	7	9	6	9	6

All useful and further described parameters with the number of used measurement sets for the group of participants belonging to the normal blood pressure class, to the elevated blood pressure class or the hypertension grade 1 class, are listed in the table 4.10. Data belonging to a normal distribution are represented with mean and standard deviation (mean (SD)) and non-normally distributed data are represented with median and interquartile range (median [IQR]).

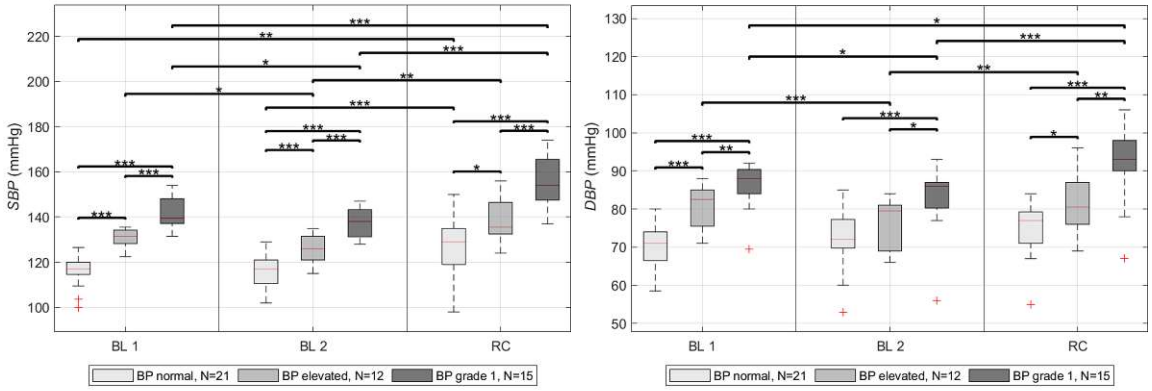
Table 4.10: Means with standard deviation in round brackets, medians with interquartile range in square brackets and number of used measurement sets of the different parameters during both baselines, the task and the recovery for the different blood pressure classes.

		Baseline 1	Baseline 2	Task	Recovery	N (#)
SBP (mmHg)	BP normal	116.43 (6.54)	115.71 (7.32)	-	127.43 (14.45)	21
	BP elevated	130.86 (4.26)	125.18 (6.06)	-	138.82 (10.46)	12
	Grade 1	141.90 (6.33)	137.53 (6.68)	-	155.33 (11.76)	15
DBP (mmHg)	BP normal	70.29 (5.89)	72.19 (7.22)	-	74.38 (7.73)	21
	BP elevated	80.05 (5.36)	75.73 (6.42)	-	80.73 (7.62)	12
	Grade 1	86.40 (5.77)	82.93 (8.71)	-	92.13 (10.01)	15
PAT (ms)	BP normal	263.69 (27.28)	258.54 (27.18)	237.15 (39.89)	247.81 (28.52)	15
	BP elevated	277.49 (36.03)	266.51 (28.27)	238.25 (36.88)	253.43 (25.34)	10
	Grade 1	248.72 (41.12)	246.58 (39.04)	233.01 (57.23)	244.12 (55.34)	12
HR (1/min)	BP normal	73.40 (10.79)	72.99 (11.17)	87.59 (16.55)	76.81 (12.20)	20
	BP elevated	70.01 (11.19)	69.32 (11.44)	93.19 (25.93)	73.40 (12.84)	11
	Grade 1	70.19 (14.89)	68.83 (13.61)	89.95 (24.36)	74.86 (15.2)	14
LF/HF (1)	BP normal	1.32 [0.69, 2.10]	1.55 [1.21, 1.96]	2.56 [1.50, 6.01]	2.53 [1.50, 3.42]	9
	BP elevated	0.71 [0.36, 2.04]	1.24 [0.83, 1.48]	2.20 [1.57, 7.64]	1.99 [0.88, 2.82]	7
	Grade 1	1.92 [0.51, 2.12]	1.18 [0.55, 1.56]	2.24 [1.56, 2.43]	2.22 [1.74, 2.68]	9
SDNN (ms)	BP normal	34.32 [26.59, 47.78]	37.40 [27.01, 44.02]	33.37 [22.35, 45.42]	45.08 [35.66, 56.59]	19
	BP elevated	25.48 [19.56, 30.51]	25.06 [23.77, 30.48]	33.04 [24.53, 59.17]	38.65 [30.15, 53.29]	11
	Grade 1	36.30 [31.23, 62.71]	34.72 [31.77, 42.20]	50.23 [38.41, 67.17]	59.68 [40.43, 77.58]	13
RMSSD (ms)	BP normal	26.62 [24.16, 41.75]	28.65 [25.75, 37.42]	29.48 [25.55, 38.21]	33.93 [27.26, 41.61]	16
	BP elevated	29.66 [22.21, 32.62]	34.82 [26.34, 39.42]	27.44 [25.13, 36.64]	28.59 [26.35, 34.07]	10
	Grade 1	38.23 [29.40, 44.43]	33.52 [31.11, 45.06]	39.28 [30.75, 50.50]	38.02 [30.79, 45.38]	11
CT (ms)	BP normal	281.17 (40.45)	283.66 (41.31)	326.36 (77.51)	299.50 (55.87)	19
	BP elevated	266.20 (37.99)	275.72 (50.55)	303.86 (59.47)	286.11 (51.48)	10
	Grade 1	295.82 (69.60)	282.77 (57.08)	359.99 (87.34)	296.07 (61.82)	14
DT (ms)	BP normal	580.22 (52.42)	578.55 (47.80)	502.63 (94.80)	551.17 (68.56)	19
	BP elevated	604.50 (42.03)	590.69 (62.21)	520.59 (87.05)	568.65 (66.56)	10
	Grade 1	561.17 (75.98)	569.79 (68.08)	469.22 (100.38)	540.12 (75.34)	14
NT (ms)	BP normal	419.78 (52.42)	421.45 (47.80)	497.37 (94.80)	448.83 (68.56)	19
	BP elevated	395.50 (42.03)	409.31 (62.21)	479.41 (87.05)	431.35 (6.56)	10
	Grade 1	438.83 (75.98)	430.21 (68.08)	530.78 (100.38)	459.88 (75.34)	14
IPA (1)	BP normal	0.83 (0.25)	0.85 (0.25)	0.55 (0.20)	0.71 (0.24)	19
	BP elevated	0.93 (0.17)	0.90 (0.21)	0.56 (0.28)	0.77 (0.23)	10
	Grade 1	0.89 (0.34)	0.89 (0.27)	0.56 (0.27)	0.68 (0.24)	14

4.5.1 Blood Pressure

Systolic and diastolic blood pressure of the different blood pressure classes were normally distributed, thus, their mean values and standard deviations were calculated and are listed in the table 4.10.

Figure 4.23a shows the systolic blood pressure for subjects with normal BP, elevated BP and hypertension grade 1. Significant differences could be seen between all groups in each phase. In each phase, *SBP* of the hypertension group exceeded highly significantly ($p < 0.001$) the group of elevated BP and the group with normal BP. The group with elevated BP also exceeded highly significantly ($p < 0.001$) the group with normal BP during both baselines and slightly significantly ($p < 0.05$) after the task. When looking at the individual groups, one could observe that all recovery values were significantly higher than the second baseline values, either highly significantly ($p < 0.001$) or mid significantly ($p < 0.01$). In the group with normal BP and those with grade 1 hypertension, the recovery values were also raised from the first baseline value with either high ($p < 0.001$) or mid significance ($p < 0.01$). In the group with elevated BP and hypertension, the two baseline periods were also significantly different ($p < 0.05$), with the second baseline phase decreasing from the first. Overall, all *SBP*s of the groups increased between the beginning and the end of the experiment. *SBP* differences of the normal BP group ($p < 0.01$) and hypertension group ($p < 0.001$) were significant, while *SBP* differences of the elevated BP group were not significant.



(a) *SBP* (mmHg)

(b) *DBP* (mmHg)

Figure 4.23: Grouped boxplots of blood pressures (mmHg) during both baselines (BL1, BL2), the task (T) and at the end (RC) apportioned to the blood pressure classes. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

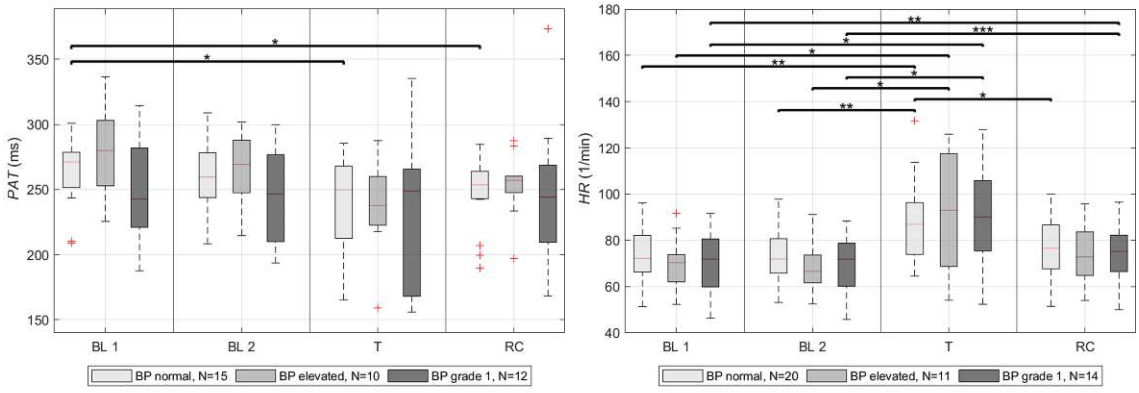
Diastolic blood pressure for the three different BP groups are presented in figure 4.23b. *DBP* behaved in a similar way to *SBP*. In the first baseline phase and in the recovery phase, all groups differed significantly from each other; *DBP* of the hypertension group exceeded highly significantly ($p < 0.001$) *DBP* of the normal BP group and with a smaller level of significance (either $p < 0.01$ or $p < 0.05$), it exceeded the *DBP* of the elevated BP group. Meanwhile *DBP* of the elevated BP group exceeded *DBP* of the normal BP group solely in the first baseline ($p < 0.001$) and during the recovery ($p < 0.05$). In the group with normal BP, there were no significant differences between the phases, but the increase in the recovery phase was still evident. In the group with elevated BP and hypertension

there were significant differences. Here, both second baseline phases decreased significantly from the first one (elevated BP group $p < 0.001$, hypertension group $p < 0.05$), afterwards, they increased significantly in both cases compared to the previous baseline phase (elevated BP group $p < 0.01$, hypertension group $p < 0.001$). In total, the *DBP* values also increased from the beginning to the end of the experiment. *DBP* between beginning and end of the group with normal BP differed, but without significance. In the elevated BP group, the final value almost returned to baseline, and in the hypertensive group, the difference was significant ($p < 0.05$).

4.5.2 Pulse Arrival Time and Heart Rate

Pulse arrival times and heart rates were assigned to the different BP classes. Since they all were normally distributed, their mean values and standard deviations were calculated and are listed in the table 4.10.

Figure 4.24a represents the pulse arrival times of the different blood pressure groups as boxplots. No significant differences could be observed between the groups, however, differences between the phases of the experiment occurred in the group with normal BP. Here, *PAT* during the task significantly decreased ($p < 0.05$) compared to the first baseline value and stayed reduced in the recovery phase, which was again significantly reduced ($p < 0.05$) compared to the first baseline. In the hypertension group, there were no changes in *PAT* during the task and recovery compared to the baseline periods; on average, the values remained the same. In the group with elevated BP, on the other hand, *PAT* decreased within the task period and slightly increased in the recovery phase, but without significance. Overall, all groups fell with their *PAT*s from the beginning to the end of the sessions. The normal ($p < 0.05$) and elevated BP ($p < 0.01$) group showed a significant *PAT* change, while the hypertension group differed only slightly but not significantly.



(a) *PAT* (ms)

(b) *HR* (1/min)

Figure 4.24: Grouped boxplots of *PAT*s (ms) and *HR*s (1/min) during both baselines (BL1, BL2) and at the end (RC) apportioned to the blood pressure classes. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

Heart rates of the BP classes are shown in figure 4.24b. No statistically significant differences between the groups could be detected here either. However, the increase in *HR* in the task phase and the decrease in the recovery phase could be clearly seen in all groups. During the task, the group with normal BP had the lowest *HR* value in this segment, *HR* of the other two groups were similarly elevated. Comparing the individual groups with each other, there were significant differences in the different phases. In all groups, the *HR* during the task was significantly different from the respective baseline periods (normal BP group $p < 0.01$, elevated BP group $p < 0.05$, hypertension group $p < 0.05$). After the task, the *HR* values dropped again in all groups, but this decrease was only significant ($p < 0.05$) in the group with normal BP. In the group with hypertension, the recovery value was highly significantly increased compared to the baseline periods (BL1 $p < 0.01$, BL2 $p < 0.001$), but in contrast to the task it had, nevertheless, fallen. In the general trend of *HR* between the beginning and the end of the measurements, an increase in *HR* could be observed. The groups with normal and elevated BP only deviated slightly but without significance. The group with hypertension, on the other hand, deviated highly significantly ($p < 0.001$).

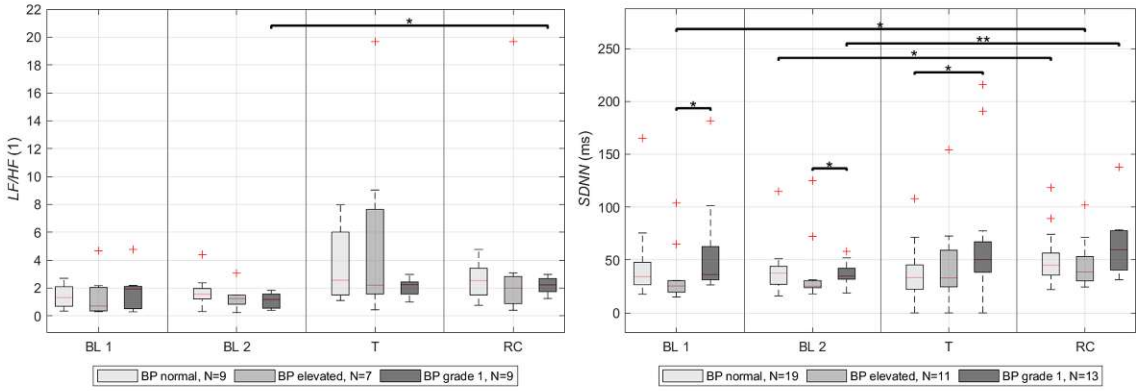
4.5.3 Heart Rate Variability

LF/HF power ratios, *SDNN*s and *RMSSD*s were assigned to the different blood pressure classes. As they did not belong to a normal distribution, their median values with first and third quartiles were calculated and are listed in the table 4.10.

*LF/HF*s for the groups with different BP classes are shown in Figure 4.25a. Again, no significant differences were found between the groups. In general, *LF/HF* increased during the task in all groups and remained elevated during the recovery phase, but without significance. Only the group with elevated BP showed a significant difference; here, *LF/HF* increased slightly significantly ($p < 0.05$) in the recovery phase compared to the second baseline. *LF/HF*s of the groups with normal BP and those with hypertension remained at the same elevated level in the recovery phase as during the task, only the group with elevated BP decreased a little in the recovery phase. Overall, *LF/HF*s of the normal BP group and the hypertensive group increased slightly between the start and end of the experiment but without significance, while *LF/HF* of the group with elevated BP returned to the baseline. Because of the small sample size per group, the results are not convincing.

Figure 4.25b represents *SDNN*s for the BP classes as boxplots. There were significant differences between the groups. During the first two baseline periods, *SDNN*s of the hypertension group increased slightly significantly ($p < 0.05$) more than the group with elevated BP. *SDNN*s of the group with normal BP showed approximately the same values as the hypertension group during the first two baselines. During the task, the values of the hypertension group increased slightly significantly ($p < 0.05$) compared to values of the normal BP group. *SDNN*s of the elevated BP group during the task laid between the hypertension and normal BP group. In the recovery phase, no significant differences were seen. However, all groups exhibited a significant increase from either the first or second baseline period to the recovery phase (normal BP group and elevated BP group $p < 0.05$, hypertension group $p < 0.001$). In the group with normal BP, there was only an increase

in the recovery phase and otherwise the values were at the same level. In the groups with elevated BP and hypertension, *SDNN*s already increased during the tasks and continued to increase in the recovery phase. Overall, *SDNN*s of all groups increased from the beginning to the end of the recordings, *SDNN* changes of the normal BP and elevated BP group reached a slight statistical significance ($p < 0.05$), meanwhile *SDNN* changes of the hypertension group reached no significance.



(a) *LF/HF* (1) (b) *SDNN* (ms)

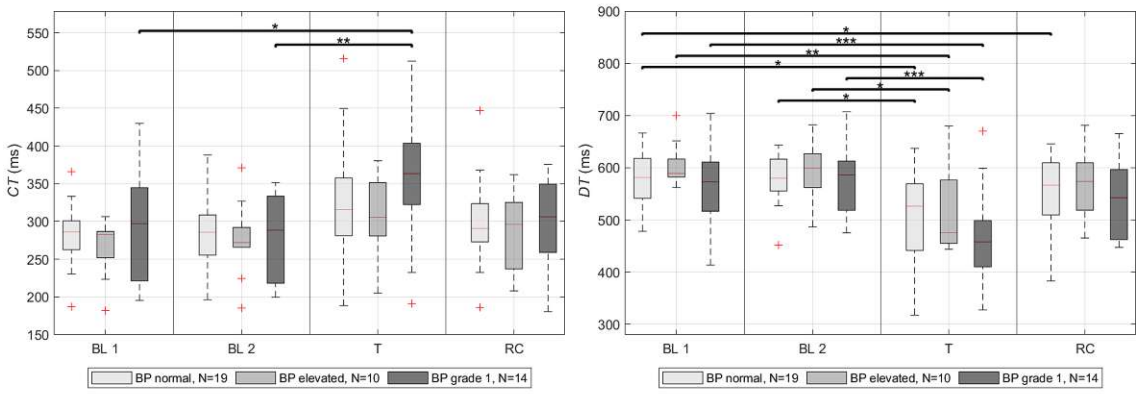
Figure 4.25: Grouped boxplots of *LF/HF*s (1) and *SDNN*s (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) apportioned to the blood pressure classes. Statistical significance: $*$ ... $p < 0.05$, $**$ ... $p < 0.01$, $***$ ... $p < 0.001$

*RMSSD*s of the BP groups showed little significant differences between the groups, but in general, *RMSSD*s of the hypertensive group were higher than those of the normal and elevated BP group. There was a significant difference between the elevated BP group and the hypertension group in the recovery phase, with *RMSSD* of the hypertension group exceeding slightly significantly ($p < 0.05$) *RMSSD* of the elevated BP group. Over the course of the experiment different trends of the *RMSSD* in the different groups could be observed. *RMSSD*s of the normal BP group exhibited the lowest values during the baselines and remained the same during the task, but increased in the recovery phase. Meanwhile, *RMSSD*s of the elevated BP group decreased with the task and stayed low during the recovery, where it was the lowest of all the groups. *RMSSD*s of the hypertension group showed no differences between the first basline, task and recovery, only the second baseline was slightly reduced. Overall, *RMSSD*s of all blood pressure groups increased between the beginning and end of the experiment, albeit without significance.

4.5.4 Pulse Wave Characteristics

Crest times, durations of diastole and notch times were assigned to the different blood pressure groups. All these values were normally distributed, so their mean values and standard deviations were calculated and are listed in the table 4.10.
Crest times of the groups with normal BP, elevated BP and with hypertension are shown in figure 4.26a. There were no significant differences between the groups, but the *CT*s of

the hypertension group exceeded the values of the other groups in all phases. *CT*s of the group with normal and elevated BP were quite equal in all phases. When looking at the individual groups, one could see a clear increase in *CT*s compared to the previous baseline periods, but without significance in all groups. Only the hypertension group differed during the task phase significantly from both baseline phases (BL1 $p < 0.05$, BL2 $p < 0.01$). After the task, the values dropped slightly again. Overall, the *CT* values increased from the beginning to the end of the recordings, but without statistical significance.



(a) *CT* (ms) (b) *DT* (ms)

Figure 4.26: Grouped boxplots of *CT*s (ms) and *DT*s (ms) during both baselines (BL1, BL2), the task (T) and at the end (RC) apportioned to the blood pressure classes. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

Figure 4.26b illustrates the durations of the diastole for the different BP groups. Again, there were no statistical significant differences between the groups. *DT*s of the hypertension group were on average lower than those of the other BP groups. In contrast, there were more significant differences between the phases within each group than within the *CT*. During the task, *DT* of all groups decreased significantly compared to their baseline periods (normal BP group $p < 0.05$, elevated BP group $p < 0.05$ and $p < 0.01$, hypertension group $p < 0.001$). After the task, the values increased again slightly. Overall, the values fell between the beginning and the end of the experiment. In the groups with normal and elevated BP, the change between beginning and end was slightly significant ($p < 0.05$), while there was no significant change in the hypertension group.

Notch times showed similar trends like the crest time. In the individual groups, *NT* values during the tasks differed significantly from the previous baseline periods with the same level of significance as within the *DT*. In all groups, *NT*s increased during the task and decreased slightly after the task. Overall, *NT* values increased between the beginning and the end, with the groups with normal and elevated BP changing even significantly.

Inflection point areas were calculated for the different BP groups. Since *IPA*s were normally distributed, mean values with standard deviations were calculated and are listed in the table 4.10.

Figure 4.27 shows *IPA*s for the different blood pressure groups. Again, no significant differences were found between the groups. However, there were significant changes between the phases of each group. All *IPA*s of the groups decreased with the task. The normal BP group decreased mid significantly ($p < 0.01$), the elevated BP group decreased slightly significantly ($p < 0.05$) and the hypertension group decreased mid significantly ($p < 0.01$) and highly significantly ($p < 0.001$) from both baseline periods. After the task, all *IPA*s increased again, with only the hypertension group reaching a slight significance ($p < 0.05$) with their increase. Overall, *IPA*s of all groups dropped between the beginning and end of the measurement. The difference in the normal BP group reached mid significance ($p < 0.01$) and difference in the hypertension group reached high significance ($p < 0.001$). The group with elevated BP dropped visibly, but did not reach significance.

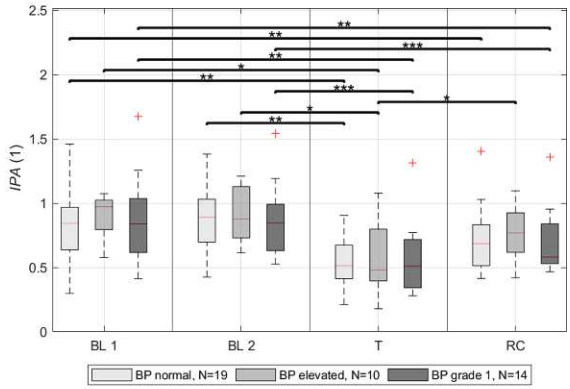


Figure 4.27: Boxplots of the averaged *IPA*s (1) at both baselines (BL1, BL2), during the task (T) and at the end (RC) apportioned to the blood pressure classes. Statistical significance: $*$ ... p < 0.05, $**$ ... p < 0.01, $***$ ... p < 0.001

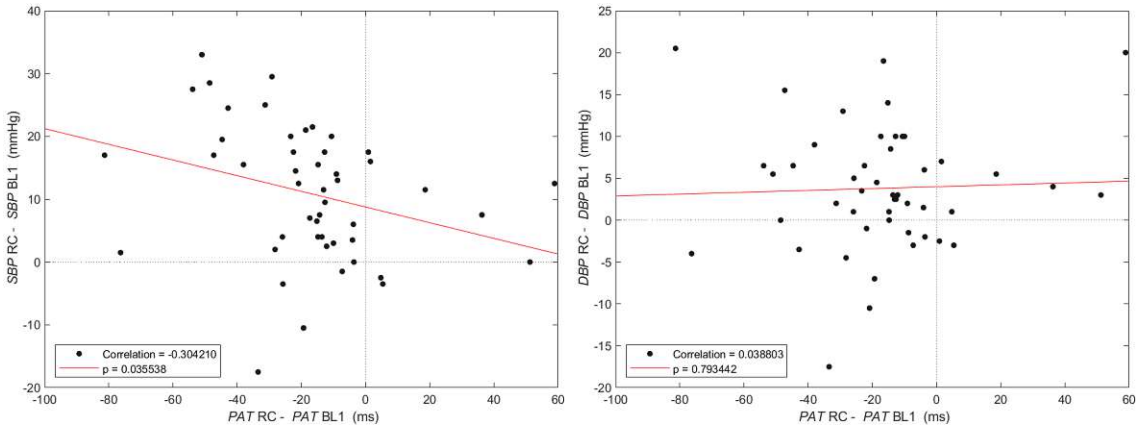
4.6 Correlation

Correlations between different parameters, for instance *PAT* and blood pressure, their differences between the beginning and end of the experiment or correlations of the inverse parameters have been calculated and are presented in the following sections. Each correlation plot indicates the correlation coefficient and the *p*-value for the statistical significance.

4.6.1 Blood Pressure and Pulse Arrival Time

To find any correlations between *BP* and *PAT*, the averaged value of the first baseline was subtracted from the averaged recovery phase value. This was done for *PAT* and both *SBP* and *DBP*, as it was shown that differences usually show better correlations than the absolute values [80].

Figure 4.28a shows the correlation between *PAT* and *SBP* changes throughout the measurements. In this case, there was a slightly negative correlation between the changes in *SBP* and *PAT* with slightly statistical significance. Dividing the measurements according to their trend in *SBP* showed that for the majority (35 out of 48) the *PAT* decreased and the *SBP* increased (above the abscissa and to the left of the ordinate). In five measurements, the *PAT* increased and the *SBP* rose (above the abscissa and to the right of the ordinate). In four measurements there was a decrease in *SBP*, although there was also a decrease in *PAT* (below the abscissa and to the left of the ordinate). In two measurements *PAT* increased and *SBP* decreased (below the abscissa and to the right of the ordinate) and in the remaining two measurements there were no *SBP* changes between the beginning and the end, but *PAT* increased and decreased.



(a) Correlation between change of *SBP* (mmHg) and change of *PAT* (ms)

(b) Correlation between change of *DBP* (mmHg) and change of *PAT* (ms)

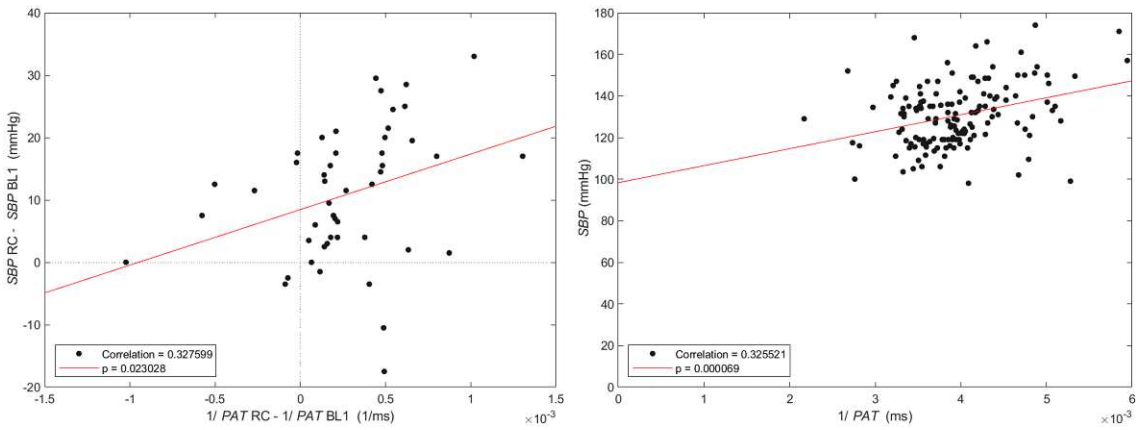
Figure 4.28: (a): Correlation between the changes of *SBP* (mmHg) and *PAT* (ms). First baseline value (BL1) was subtracted from the recovery value (RC).
(b): Correlation between the changes of *DBP* (mmHg) and *PAT* (ms). First baseline value (BL1) was subtracted from the recovery value (RC).

For the change in *DBP*, on the other hand, there was no significant correlation, as seen in figure 4.28b. However, the majority of the measurements were still above the abscissa and to the left of the ordinate, so *PAT* decreased and *DBP* increased. In one fifth, both *PAT* and *DBP* decreased at the same time (below the abscissa and to the left of the ordinate). In six measurements *PAT* and *DBP* values increased together (above the abscissa and to the right of the ordinate) and in two measurements *PAT* increased but *DBP* decreased (below the abscissa and to the right of the ordinate). As with *SBP*, in two measurements there were no changes in *DBP* but a simultaneous decrease in *PAT*.

Besides the blood pressure difference and the *PAT* difference, the correlation of the inverse *PAT* and blood pressure was also investigated, since it was reported in [4] that the inverse shows a linear relation over a wider range. For this purpose, the inverse of the *PAT* changes between recovery and first baseline were calculated and their correlation with the difference of the blood pressure changes between recovery and first baseline were calculated.

Figure 4.29a shows the correlation between the *SBP* changes and the corresponding inverse *PAT* changes between beginning and end of the experiment. A weak positive correlation could be seen between the *PAT* inverse and *SBP*, with slightly statistical significance. The majority of the measurements (35 out of 48) increased with their *SBP* values while their inverse *PAT* values also increased (above the abscissa and to the right of the ordinate). Conversely, only in three measurements *SBP* rose with decreasing inverse *PAT* (above the abscissa and to the left of the ordinate). In four measurements, inverse *PAT* increased with decreasing *SBP* (below the abscissa and to the right of the ordinate) and in two measurements, inverse *PAT* and *SBP* decreased (below the abscissa and to the left of the ordinate). As with the normal correlations, in two measurements *SBP* did not show an increase or decrease but inverse *PAT* increased in one measurement and decreased in the other one.

No correlation can be detected between the *DBP* values and the inverse *PAT* changes between the beginning and the end of the study. The corresponding figure can be seen in the Appendix A.2.3.



(a) Correlation between changes of *SBP* (mmHg) and changes of inverse *PAT* (1/ms)

(b) Correlation between *SBP* (mmHg) and inverse *PAT* (1/ms)

Figure 4.29: (a):Correlation between the changes of *SBP* (mmHg) and changes in inverse *PAT* (1/ms) , recovery value subtracted from first baseline value.
(b):Correlation between *SBP* (mmHg) from BL1, BL2, and RC and inverse *PAT* (1/ms) from BL1, BL2, and RC.

In addition, the correlation between *SBP* and inverse *PAT* was also considered. For this purpose, data from the first and second baseline phase were used, as well as data from the recovery phase. No differences were calculated, instead, the averaged data of each participants were selected. The correlation between the *SBP* and the inverse *PAT*s can be seen in figure 4.29b. Here, a weak but highly significant correlation between the *SBP* and inverse *PAT* in the baseline and resting phases was evident. This correlation was higher than the correlation of the differences between recovery phase and baseline phase.

A weaker but still significant correlation could be also observed for *DBP* and the inverse

PAT. The corresponding figure can be seen in the Appendix A.2.3.

4.6.2 Pulse Arrival Time and Heart Rate

Correlations between *PAT*s and *HR*s during the different phases of the experiment were also examined. For this purpose, the averaged values for each experiment phase were used and the two baseline periods were combined. The correlation plot with correlation coefficients and significance p-values for the different phases can be seen in the figure 4.30.

At the beginning of the study, i.e. during both baseline periods, *PAT* values did not correlate with *HR* values. The correlation coefficient was slightly negative, but without statistical significance. During the task, the correlation decreased further and it was still not significant. In the recovery phase, however, the values correlated highly significantly with each other, the correlation coefficient was negative, i.e. the *HR* decreased with longer *PAT*.

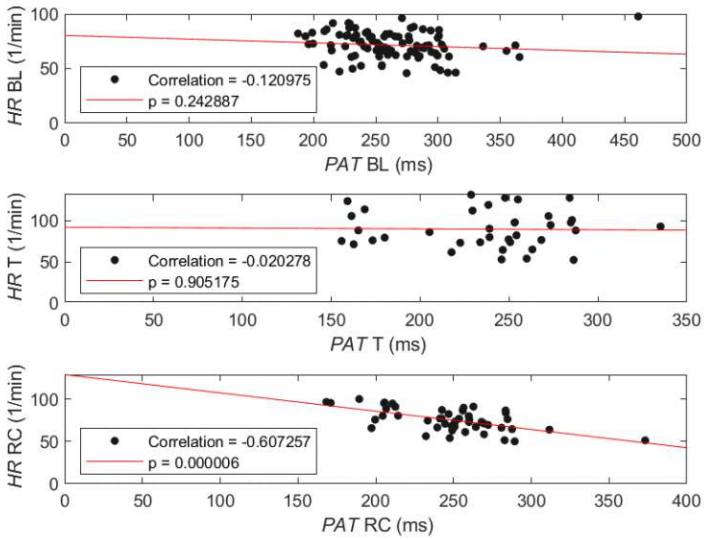


Figure 4.30: Correlation between averaged *PAT* (ms) and *HR* (1/min) at both baselines (BL), during the task (T) and during the recovery (RC). Correlation coefficient and statistical p-value.

5 Discussion

The purpose of this thesis was to investigate the differences between pulse arrival time, heart rate, blood pressure, HRV and pulse wave characteristics before, during and after a mental or physical task in hypertensive subjects. Participants of the study had to perform a modified DemTect test or climb stairs. Another aim was to evaluate the difference in parameters between different groups in addition to the general course of the parameters, so the participants were divided according to the nature of the task, their sex, age and blood pressure classes. In addition, correlations between systolic and diastolic blood pressure with pulse arrival time were examined, as well as correlation between pulse arrival time and heart rate.
All parameters except blood pressure were measured in all phases of the study, i.e. first and second baseline, during the task and in the subsequent recovery phase. Blood pressure was only measured in the two baseline periods and in the recovery phase, as the obtained values would be rich in artefacts and would be unusable, and the participants should not experience any further impairments.

5.1 General Time Course

During a task of mental or physical nature, physiological responses are triggered through the autonomic nervous system (ANS) [8, 70], which can be seen in various vital parameters. As seen in section 4.1, *SBP*, *HR*, *LF/HF*, *CT*, and the associated *NT* increased with the task, whereas *PAT*, *RMSSD*, *IPA*, *sVRI*, and *DT* decreased. In the case of the *SDNN*, the opposite results could be shown, with the task *SDNN* increased.

Between the beginning and end of the measurement, *SBP* increased. The *DBP* increased only to a smaller extent. In the guidelines for the management of arterial hypertension [20], the greater increase in *SBP* and the increase in *DBP* to a lesser extent has been documented as well, although it is also important to note that DBP is calculated differently depending on the method, device and algorithm [20]. Interestingly, *SBP* of the two baseline periods differed and this difference continued to occur in the different groupings of the large population, with *SBP* decreasing in the second baseline period in the male participants, in the older participants and in the elevated BP group as well as in the hypertension group. Perhaps the affected participants had to get used to the measurement environment and needed a longer time to adapt.

As expected, with increasing *SBP* in the task period, *PAT* decreased, and increased again afterwards but could not reach the starting value again. Since a significant increase in *BP* leads to an increase in vascular tone, and thus to an increased Youngs modulus of the arterial wall, the *PWV* increases and the *PAT* shortens [19, 31]. Already in the study

by Vlachopoulos et al. [11], a prolonged deteriorating of the the aortic stiffness and wave reflections with a short preceding period of stress is shown, based on induced endothelial dysfunction which regulates the arterial stiffness. However, the tasks were mixed between physical and mental nature in this part of the evaluation, as well as elderly and hypertensive people, thus those factors might contribute to the prolonged decrease in *PAT* as well.

HR is mainly controlled by the sympathetic and parasympathetic branches of the ANS and if a stress stimulus is present, the SNS activity increases and causes an augmentation of the excitation frequency of the sinoatrial node, thus, the *HR* will rise [9], as it was the case in this experiment. Upon task completion, *HR* decreased, but a fully recovery could not be regained.

A rise in SNS activity can be detected not only in the increased *HR*, but also in the HRV, i.e. *LF/HF*. During the task, *LF/HF* rose and stayed afterwards elevated, which indicates an increased sympathetic activity and/ or a decreased vagal activity [81], depending on how the *LF* component is interpreted. Besides the increase in *LF/HF*, *RMSSD* slightly decreased during the task, indicating reduced vagal activity [67, 82]. This substantiates the increased SNS activity and decreased PNS activity during the task. Since *LF/HF* remained elevated in the recovery phase and had only slightly decreased, it can be assumed, that the SNS activity has not declined so quickly or that the PNS activity did not yet take over. However, between the beginning and end of the measurement, *RMSSD* increased significantly, suggesting that the parasympathetic drive did increase.
SDNN revealed contradictory results, it already increased during the task. Since *SDNN* expresses the components which are responsible for the variability [62, 63], a high HRV corresponds to an elevated *SDNN* value and usually is accompanied with a lower *HR* [67]. Hence, a reduced *SDNN* value would actually be expected in the task phase, as this is when the highest *HR* was measured. Given, that an elevated *SDNN* score is also an index of physiological resilience to stress [9], it appears that the participants were not unduly stressed, which could be attributed to the different tasks. After the task, the expected increase occurred, causing the overall *SDNN* between beginning and end to rise.

With the increase in vascular tone, not only *PWV* increases, but it is also said that the appearance of the PPG signal is changing [72], thus stress or physical exertion changes consequently the shape of the PPG signal, due to changes in the ANS [69]. During the task, the *CT* and *NT* rose, and fell again in the recovery phase. As the *DT* is the counterpart to the *NT*, it behaves in the opposite way. One would actually expect the opposite for the *CT* and for the *NT*, respectively, i.e. a drop in these parameters with the task, as the *PWV* rises due to the increased vascular tone and stiffness [71], and the peak can thus be reached more quickly. Since *NT* is somehow regarded as a time index of the reflected pulse wave arrival, it contains information about the wave reflections. A smaller *NT* indicates early wave reflections and augmented pressures [70], which is in contradiction with the increased *BP* and decreased *PAT* in this experiment. Also several study results [69, 71, 70] suggest that *CT* and *DT* decrease in a stress period. However, it must be noted that each pulse wave has been normalized to the length of one second in this study, thus decreased *NT* has to be accompanied by an increased *DT* and vice versa, and in the above-mentioned

studies, it is not clear, if and how the data were normalized and thus, the extend of wave reflections cannot be compared here either.

Stress is said to also change the amplitude of the PPG signal [73], therefore, indices containing amplitudes or areas under the curves can be indicative of stress. *IPA* in this study decreased during the task and increased again in the recovery phase. Similar results were found in the study by Celka et al. [71]. Considering the two areas of *IPA* as systolic and diastolic pulsatile components as in [19], a small difference between the two, i.e. a ratio close to one, indicates that the arterial system efficiently generates a smooth blood flow. The drop during the task would therefore indicate that smooth blood flow could no longer be achieved efficiently in the periphery, but it improves in the recovery phase again.
Similar trends were obtained regarding the *sVRI*, although studies of Zhang et al. [73] and Lyu et al. [72] demonstrated an increase in *sVRI* with the task. *IPA* and *sVRI* are very similar in their calculations, also their trends were very similar. A non-negligible difference between these two variables is the magnitude of the standard deviation. *IPA* had the smallest variance, implying that the values did not differ very much between participants, thus this work will also focus on that, and not on *sVRI*.

In general, it can be said that the reactions to the stress situations could be seen well and many parameters recovered afterwards again. Here in the general part of the evaluation, the influence of hypertension or elevated BP was not yet visible, since about half of the participants of this study had normal BP and thus balance the parameters apparently.

5.2 Task

The comparison of the parameters between the mental and physical nature of the task is shown in section 4.2. The two groups each consisted of approximately half younger and half older participants, and the blood pressure classes were similarly divided. Throughout the study, more male participants took part than female participants, hence more male participants performed the mental and physical task.
The physical task elicited greater cardiovascular changes then the mental task, with *SBP*, *HR*, *LF/HF*, and *CT* increasing more and *PAT*, and *IPA* decreasing in the physical task group more. HRV time domain data did not show clear and consistent results, but the trend that HRV dropped more during physical exertion is evident, at least in *SDNN*.

Regardless of the nature of the task, *SBP* increased after the task. *SBP* after the physical task was slightly higher. There was also a difference in *DBP* after the mental and physical task, as the *DBP* of the mental group increased and was clearly different from that of the physical group, which did not show any pronounced changes throughout the experiment. The greater increase in *SBP* after the task can be explained by taking a closer look on the effects of exercise on the cardiovascular system. Physical activity inhibits vagus nerve impulses to the heart and activates the SNS. This is followed by an increase in *HR*, cardiac output, arterial pressure, O_2 consumption, and contractile force of the heart muscle. Vascular resistance increases in inactive muscles and decreases in active muscles [13], thus

blood vessels of the working muscles dilate and the total peripheral resistance decreases, the *DBP* theoretically decreases [15]. However, in this experiment, the *DBP* did not show any decreases after the task. During a mental challenge, the SNS gets also activated leading to an increase of *HR*, *BP* and the release of catecholamines [11, 12]. Depending on the nature of the mental task, different haemodynamic response patterns are elicited [68]. Since in this mental task no other muscles were activated – the participants did not even have to write anything down – the resulting *BP* did not rise as much. However, as only values after the task were measured, it is not known exactly what the data looked like during the tasks, but it might be assumed that the trend in the recovery phase was also the same as in the task phase.

The stronger increase in *SBP* of the physical group could also be clearly seen in the *PAT*, as *PAT* decreased during the physical task, whereas in the mental task there were no significant differences. *PAT* is known to correlate better with *SBP* than with *DBP* [18, 32, 46, 83]. Attention should be paid to the *PEP*, which can make a significant contribution to *PAT* [42], and falsify trends. *PEP* could not be calculated in this study, since only ECG and PPG signals were continuously recorded. It is also interesting that *PAT* of the mental group did not differ between the different phases, although *BP* showed changes and it was stated in many studies [11, 12, 33], that arterial stiffness increases with a mental stress, thus *PAT* should decrease. This could indicate that the relation between *BP* and *PWV* is not as simple as assumed and that many other factors are involved, for instance, sex, age or CV risk factors like hypertension. Since more elder participants and more hypertensive participants performed the mental task compared to the physical task, it could be that age and CV risk factors influence indeed the relation between *BP* and *PWV*.

As expected, *HR* increased more during the physical task to compensate the decreased total peripheral resistance and the increased cardiac output [15]. During the mental task, *HR* also increased and almost returned to the baseline value, while *HR* of the physical group was significantly increased at the end. The difference in *HR* between the physical task and the recovery period was over 20 beats per minute, so it is understandable that the *HR* has not yet managed to return to baseline within the five minute recovery period. An increased reactivity to the mental task and a decreased recovery may be associated with an impaired cardiovascular status [66], however, since there was no strong reactivity here, the participants tend to not exhibit cardiovascular deterioration, even though many of them experienced elevated BP and hypertension.

With both tasks, SNS activity theoretically increases and PNS activity decreases. In the physical task, along with a rise in *HR* and *SBP*, *LF/HF* increased and *SDNN* decreased, while with the mental task, *LF/HF* and *SDNN* increased slightly. Thus, in the physical task, the SNS seems to be more activated than in the mental task. Although *LF/HF* was also increased in the mental group and thus, the SNS is likely to be more activated here as well, *SDNN* increased simultaneously, indicating increased HRV and resilience [9]. Vagal activities [81] could not be observed in the data, since *RMSSD* barely changed. Consequently, in both tasks, SNS activity increased, within the physical task the rise was more pronounced, but PNS activity appeared to have remained the same in both cases.

The recovery after the tasks looked different for the two groups. The physical task group suggested increased HRV, due to an increased *SDNN*, and sympathovagal balance tended to a withdrawal of SNS activity and/ or reactivation of PNS, since *LF/HF* decreased although RMSSD was unchanged. In the mental task however, *LF/HF* remained at the same level as during the task, only *SDNN* increased slightly. The steady *LF/HF* in the mental group would indicate a shift towards the SNS as before, but the increased *SDNN* value points to a recovery in the HRV. Overall, it can be said that there were no severe HRV changes or deterioration during the mental task, but slightly more pronounced changes occurred during the physical task.

During the physical task *CT* and *NT* increased more and *DT* decreased more than during the mental task. One can see that the physical task triggered stronger changes, but the values recovered by the end. In the mental task group, final values differed significantly from the initial values, their initial values could not be reached again and they would have needed a longer recovery period. The increased reactivity after a mental task was already seen in the study be Reppel et al. [33], where two hours after a physiological stress, the central *SBP* was increased and the *DBP* was already decreasing, leading to a delayed increase of the central pulse pressure and thus, to a worsening of pulse pressure amplification, where the coronary perfusion is impaired.

IPA during the physical task decreased more than during the mental task. Since the area ratio is mainly influenced by the strength of the pulse wave reflections [84], a smaller *IPA* would indicate an earlier return of the reflected wave, which amplifies the systolic part of the wave and thus increases the left ventricular afterload [11]. The wave reflections play an unfavourable role in both tasks to the detriment of the afterload and coronary blood perfusion. After the physical task, *IPA* indicated a reduction of the amplified systolic part, which ultimately improves coronal blood flow. Of interest is the remaining lower *IPA* after the mental task, which suggests that mental tasks have a longer effect on the CV system. As with *PAT* and *PWV*, factors such as the age, sex and hypertension may also play a role in the decreased recovery, since the mental and physical groups consisted of all ages, sexes and all BP classes.

In summary, stronger CV responses were triggered during the physical task with an increased SNS activity than during the mental one. After the physical task CV parameters showed a quick recovery again, however, in the mental group, the unchanging *PAT*, *HR*, *LF/HF*, *IPA* and pulse wave time values, between task and recovery, indicated a poor recovery.

5.3 Sex

Differences in the parameters between the male and female sexes are shown in section 4.3. The number of men and women were not equally divided. In the larger group, namely the male participants, more participants performed the mental task than the physical task, and also more participants were older than average. The blood pressure classes, however,

were equally divided with approximately one third belonging to each BP class. Among the women, the tasks were equally divided and the age distribution was also almost the same, only the BP classes differed. Half of the female participants had normal BP and the other half had elevated BP and hypertension. Thus, the mental task and age could shift some parameters in the men.
Overall, *SBP*, *HR*, and *CT* increased more and *PAT* as well as *IPA* decreased more in women than in men, indicating increased SNS activity within the female participants. However after the task, women had lower *LF/HF*s and higher *RMSSD*s and *SDNN*s, which in turn suggests a more pronounced rise in PNS activity than in men.

Throughout the experiment, *SBP* increased after the task in men and women, only *DBP* of the female group did not increase. *SBP*s of women were throughout the experiment higher than those of men. Normally, one would expect higher *BP* values in men and lower in women [85], however, after the menopause *BP* of women increases. Since the average age was around 64.6 years, it is very likely that women, who participated in this study, were already post-menopausal and the increased *BP* can therefore be explained. In addition, half of the female participants suffered from high BP, so an increase in the *SBP* of women was to be expected. However, it is interesting to note, that the *DBP* of the women did not increase significantly after the task. In men, more participants had performed the mental task and since there was an increase in *DBP* during the mental task as seen in section 4.2, this might also be a reason for the increase in *DBP* in men.

Across the board, *PAT* of women were lower than in men, which could be due to the shorter distance between the heart and the finger. Also of interest is that the *PAT* of men did not differ during the task, recovery and baseline phases, they did not seem to be susceptible to stress, but women were. This can also be seen in the *HR*, as the *HR* of the men was lower than that of the women during the task and during the recovery phase. It is also known that women are more susceptible to stress [67] and generally have a higher *HR* [48, 67, 81], thus, the results here are consistent.

At the beginning of the experiment, women showed increased HRV and increased resilience [9, 62, 81], since their *SDNN*s were higher than in men. However, *LF/HF* and *RMSSD* were at the same level, so there was no significant dominance of the PNS in the resting phase, although it would be expected in women as described in [67, 81]. In the task phase, sympathetic influences increased in both groups, as both *LF/HF*s increased. Nevertheless, a decrease in PNS activity could not be seen, as *RMSSD*s remained the same and *SDNN*s increased. Due to slightly higher *RMSSD* and *SDNN* values in women and higher *LF/HF* in men, it appears that there is a higher sympathetic tone in men than in women. In the recovery phase, there was an increased vagal tone in women, e.g. *LF/HF* decreased, *SDNN* and *RMSSD* increased, whereas men showed increased sympathetic tone, as *SDNN* and *RMSSD* were lowered and *LF/HF* was higher at the end. The increased *SDNN* during the task and recovery also occurred in the mental group, but after the task the *RMSSD* also increased and here the *RMSSD* of men remained at the same level. Thus, sex does indeed seem to have an impact on the ANS activity.

In all phases of the experiment, *CT*s and *NT*s were higher in women than in men, *DT*s fell more sharply in the female group. Since the *PWV* of men is higher compared to women, according to [86], this would explain the shorter *CT*s and *NT*s, however, since the data were differently calculated they cannot be compared further.

*IPA*s of the female participants were lower throughout the experiment compared to *IPA*s of male participants, so the CV system of men could provide smoother blood flow more efficiently than that of women [19]. Values of the male participants recoverd more quickly than in women, suggesting that men cope better with stress than women [67], as the PPG contour does not change as much for men. Another reason could be that more men had performed the mental task and *IPA* did not change as much in the mental task as in the physical task.

Although overall, more men had elevated BP and hypertension than women which could influence the values and trends here, it does not seem to be the case, because *SBP* of men was lower than that of women, as well as the *HR*. As a result, it is not possible to determine clearly whether SNS or PNS activity predominates in women or men, but it can be seen, that men were coping better with the tasks and recovered more quickly than women.

5.4 Age

The comparison of the parameters for the participants who were older or younger than the mean age of 64.6 years are shown in section 4.4. The group of older participants was a little larger, consisted of more participants who had performed the mental task and more male participants. The different BP classes were equally divided within the elder participants, with approximately one third belonging to each BP class. In the younger participants, the two tasks and the gender were well divided, but the majority of the younger participants had normal BP.
Generally speaking, there were not many significant differences between the older and younger participants. *SBP*, and *HR* of the older participants increased a little more and *DBP*, *PAT*, and *IPA* decreased a little more. On the other hand, HRV data suggests increased vagal tone in the older age group, with *LF/HF* being smaller and *RMSSD* being higher than in the younger age group.

*SBP*s of the older participants were greater than that of the younger participants and *DBP*s of the older participants were lower than that of the younger participants throughout the recordings. It is already known that *BP* increases with age [5, 15, 21, 87]. The mechanisms of action behind this are related to remodelling processes of the vascular wall [13, 15], which consequently loses its elasticity and becomes stiffer, so the wave reflections travel back faster and increase the systolic range. In addition, age increases the likelihood and duration of the effect of numerous environmental factors that increase *BP* over time, i.e. alcohol consumption and increased salt intake [21]. A weaker reaction to the stress situation, as in [19], cannot be observed in the elderly in this study. The group of older participants consisted more of men and participants who had performed the mental task,

despite that *BP* of the mental task and males, did not show a large increase in *SBP*, a clear increase in *SBP* within the elderly was visible.

Considering the higher *SBP*s, and the probably ongoing changes in composition of the arterial walls [13, 15], the decreased *PAT*s of the group of older participants are conclusive. A decrease in *PAT* with age would thus be expected, since *PWV* and *BP* increases with age, but many studies have shown that *PAT* actually increases with age [48, 88], since *PAT* includes *PEP* and this electromechanical delay increases with age [6]. Interestingly, *PAT*s of the elder participants did not fall sharply in the task period nor rose afterwards, but *PAT*s of the younger ones did. Reasons for this could be the increased *PEP*, which can influence and compensate for changes in *PAT*s, or that older people do not react to a stress situation with an additional increase in *PWV* – they seem to be resilient.

Overall, *HR*s of the elderly were higher than in the younger participants. During the task, both groups showed an increase in *HR* and a subsequent decrease. Thus, it seems that older and younger participants reacted in the same way to a stressful situation and neither of them responded weakly to a stressful situation.

According to the work of Zeh [81], theoretically, there is a shift in ANS ratios with age, as vagal tone decreases and thus *LF/HF* would actually increase, however, this cannot be observed here. During the stress situation, *LF/HF* of the younger increased more, meanwhile, *SDNN*s and *RMSSD*s were equally up. Thus, apparently in younger subjects SNS activity is increased while PNS activity remained the same. In the elderlies, a weaker response to the task occurred, since their *LF/HF*s and *SDNN*s increased only slightly. Thus, the group of older participants responded indeed to the task, but the SNS was not activated as strongly as in the younger ones. In the recovery phase, the older participants showed a reactivation of the PNS with increased *RMSSD* and *SDNN*, while the SNS was probably still active, because *LF/HF* was still increased. In the younger participants, however, it seemed as if the SNS activity was decreased but the PNS was not yet active, because *RMSSD* was still decreased and *LF/HF* was still increased, while *SDNN* was increased.

*CT*s of the older participants were consistently higher than *CT*s of the younger ones, and *DT*s of the elderlies were dropping more than those of the younger ones. During the task phase, *CT*s and *NT*s of both groups increased and *DT*s decreased, although one would expect the inverse trend [71], since *PWV* increases with age [13, 15] and the reflected wave overlaps earlier in time, thus the time to the systolic peak or to the dicrotic notch might change and can become shorter. The differences between the older and younger participants are consistent, although in the wrong direction, but this is related to the mode of calculation and normalization.

The younger participants exhibited a greater drop in *IPA* with the task, suggesting that they were more affected by stress and reacted more with increased vascular stiffness than older participants, since with increased *PWV* the timing of the reflected wave changes [13, 15] and the area under the systole increases. After the stressful situation, *IPA*s of the younger participants increased more than that of older participants, so it seems that

elderlies did not react as strongly to a stressful situation but needed a longer time to recover.

In summary, it can be said that elder participants did not react to stress with all parameters and their reactions were usually lighter than in younger participants. However, they showed a reduced recovery to stress, which is known from literature [66]. Since similar results were obtained for the group of the mental task and male participants, and since the group of elderly consisted more of men and of more participants performing the mental task, perhaps the results are dependent on them and not only due to age.
It should also be stressed that the mean age was 64.6 years, so the distinction between younger and older people should be treated with caution. Participants who are 60 years old, for example, also belonged to the younger age group, although in other studies they would already be classified into an older age group.

5.5 Blood Pressure Grade

Cardiovascular parameters of the groups with normal and elevated BP as well with hypertension are shown in 4.5. The different BP classes were well divided in terms of age and gender distribution, only in the elevated BP group the majority performed the mental task and only a quarter performed the physical task.
There were significant differences in *SBP*, *DBP* and HRV data between the different BP classes.

Although this study was performed with hypertensive participants, one can see in the blood pressure data that some of them had normal *BP*s. Many of the participants were already taking medication for hypertension and so it seems that some of them did not have a hypertensive character. The variety of *BP* and thus the different BP classes can be seen very well in the *SBP* and *DBP* data, because the boxplots are lined up in stages, at 120 mmHg the group with normal BP, at 130 mmHg the group with elevated BP and at 140 mmHg the group with hypertension grade 1. *DBP* also showed the different classes, normal BP below 80 mmHg, elevated BP at 80 mmHg and hypertension above 80 mmHg. *SBP*s increased in all groups after the task, *DBP*s of the group with elevated BP and with hypertension increased as well, while the *DBP* of the group with normal BP hardly changed after the task.

Despite significant differences in *SBP* between the different BP groups, there were no differences in *PAT* between the BP groups. *PAT*s of the hypertensive group were consistently lower in the resting phases than those of the other groups. Since the vessels become stiffer in hypertension [13, 33, 89], the lower *PAT*s of the hypertensive subjects are consistent. It is interesting to note that the *PAT* during the task phase and the recovery phase of the hypertensive subjects did not change at all in relation to the two baseline phases. Now it could be that the compliance already takes on such a low value at rest that it can no longer decrease during a stress situation, and thus it looks as if the participant is no longer reacting to stress. A study [89] suggests that the peripheral muscular arteries such as the radial artery (arteries that are mostly involved for the PPG signal at the fingertip [5]) are not as strongly affected by hypertension or age as the central arteries, and one could

therefore conclude that the *PAT* does not change within this location.
It is also interesting that the normotensive group and the hypertensive group were on the same level in the different phases of the experiment and that *PAT*s of the group with elevated BP were higher in the resting phases and lower in the task phase. The medication may be responsible for the same behavior of the normo- and hypertensive group.

There were also no differences in *HR*s between the groups, i.e. *HR* of all groups increased in the task phase and then decreased again. An increase in *HR*s among participants with elevated BP or hypertension could not be observed. Since most of the participants were already taking medication for hypertension or other CV diseases and many of them have a HR-lowering effect [21], the results here seem to be consistent. However, it can be seen that the *HR* of the group with hypertension and those with normal BP were consistently equal, only the group with elevated BP had a lower *HR* in the resting phases and a slightly higher *HR* in the task phase.

Many hypertensives are in an autonomic imbalance with an increased SNS activity and decreased PNS activity [21, 62]. Accordingly, *LF* power would increase and parasympathetic parameters would decrease [62, 81]. The HRV data from this study cannot reinforce these results. At the beginning, no increase of the *LF/HF*s of the group with elevated BP or hypertension was seen, but an increase in *RMSSD*s in these groups, as well as a decrease in *SDNN*s of the group with elevated BP. Interestingly, *SDNN*s of the group with normal BP and hypertension were on par and higher compared to *SDNN* of the elevated BP group. It is possible that the antihypertensive drugs also affected the SNS or PNS activity, resulting in an increase in the PNS or a decrease in the SNS activity.
*LF/HF*s increased during the task in all groups, meanwhile an increase in *SDNN* during the task was only observed in the hypertensive and elevated BP group, suggesting that participants were not too taken by these tasks, although *HR* was increased. Vagal drive decreased during the task in the elevated BP group and increased in the hypertension group. In the recovery phase, the hypertensive group indicated good recovery, mainly because their values did not show pronounced deterioration, while the group with elevated BP indicated poor recovery. Poor recovery after a task is associated with poor CV status and risk of hypertension [66]. It may be that many of the participants with elevated BP are on medication, and those could influence the ANS and the recovery. Meanwhile the high *RMSSD* value of the hypertensive group seems to indicate an improvement in ANS, although only a few of them took medication.

Pulse wave times of the group with normal BP and those with hypertension behaved the same, at least in the first two resting phases, i.e. their *CT*s and *NT*s were higher than those of the group with elevated BP and their *DT*s were smaller. With the task, however, *CT*s and *NT*s of the hypertensive group increased the most and *DT*s decreased the most. Although the values were not comparable with the literature, it can nevertheless be seen that the pulse wave reflections were pronounced differently in the different BP classes.

Overall, *IPA*s of the three groups behaved in the same way. *IPA* of the group with normal BP was expected to have the highest score and can provided smoothly and efficiently blood

flow [19], but instead the elevated BP group exhibited the highest *IPA*. The hypertensive group showed the smallest *IPA* recovery after the task, followed by the values in the normal BP group and those of the group with elevated BP. Since hypertension is accompanied by an increase in *PWV* [13, 86], the pulse wave is reflected faster and already overlaps with the systolic part. As a consequence, the area under the pulse wave of the systolic part becomes larger and the *IPA* decreases, thus the results are partly consistent. It seems that the hypertensive group took longer to recover, at least according to their pulse wave shapes.

In summary, resting values for the normal and hypertensive groups were almost always equally up. During the tasks, the different groups reacted differently, participants with hypertension reacted only with changes in *BP*, *HR*, HRV parameters, and *IPA*, while the other groups also reacted to the stress with changes in *PAT*. In the recovery phase, the hypertension group exhibited the poorest recovery parameters.

5.6 Correlation

Different correlation possibilities were calculated and can be seen in section 4.6. Correlations between *SBP* and *PAT* values always showed a weak correlation that reached significance in every constellation. The correlations between *DBP* and *PAT* did not reach significance in any constellation.

Since *PAT* can track *BP* changes [5] and the differences between the beginning and end of a measurement can also reduce intersubject-variability, correlation between *SBP* differences and *PAT* differences were calculated. However, since the correlation between *SBP* and *PAT* differences was too weak and that of *DBP* and *PAT* was almost zero, no serious conclusions could be drawn from one parameter to the other. *PAT* includes the *PEP* [5, 28] and it can account for a large proportion of it. Since medication for hypertension or CV diseases can affect the left ventricular isometric contraction time [31], they can strongly influence *PEP* and furthermore *PAT*. Many participants of this study were on medication and have other CV diseases, therefore it could become apparent that *PEP* had been strongly modified and therefore, the correlation between *PAT* and *BP* was weakened.
Many studies also report a very slight to non-existent correlation between *PAT* and *DBP* [4, 6, 18, 30]. The reasons for this vary but most argue that *DBP* varies less than *SBP* [4, 42] and that *SBP* and *PAT* depend both on vascular functions and ventricular contractions [43, 83], thus the correlation between *SBP* and *PAT* is higher.

Studies also showed that the *PWV*, or general the inverse *PAT*, has a better correlation with *BP* than time [4, 37, 47]. Correlations between the inverse *PAT* differences and *SBP* differences showed a slightly stronger correlation than that between the *SBP* and *PAT* differences. Again, no correlation between the inverse *PAT* and *DBP* differences was found. Using the averaged *PAT* and *BP* values, a highly significant slight correlation between the inverse *PAT* and *SBP* was found. Again, no correlation was found between the inverse *PAT* and the *DBP* of the averaged data. Since the inverse *PAT* and *BP* are supposed to have a good linear correlations over a wide range [37], it would have been interesting to

include the task values. Unfortunately, no blood pressure was measured during the task, only PPG and ECG, thus the correlation between *SBP* and the inverse *PAT* in this phase remains unknown.
The two correlation coefficients between the inverse *PAT* and *SBP* difference and the inverse *PAT* and *SBP* of the averaged parameters were only slightly different from the correlation coefficient of the *PAT* differences and *SBP* differences, thus it cannot be clearly said that inverse *PAT* had a better correlation.

The fact that some participants deviated from the general trend, i.e. *PAT* decreased with increasing *SBP*, could be seen very well in the different groupings. The groups who performed the mental task, who were older than average, who were men, or those with elevated BP and hypertension, showed an increase in *SBP* but little to no increase in *PAT*. Thus, *PWV* or arterial stiffness did not appear to be the main component of this relationship. Already Gesche et al. [46] noted, that it is difficult to determine to what extend vascular stiffness represents *BP* and to what extend age- or disease-related changes influence arterial stiffness. Indeed, in addition to *BP*, other factors such as sex, age and CV risk factors like hypertension can also influence the *PWV* [5, 42, 46] and thus the *PAT*.

In addition correlations between *HR*s and *PAT*s were also investigated for the different phases of the experiment. Interestingly, there was no correlation in the first two baseline phases and during the task, but a highly significant negative correlation was observed in the recovery phase. Since *PEP* increases with a falling *HR* [5, 6, 47] and after the task *HR* decreased again, it seems reasonable that this relationship can be explained by an altered *PEP*. However, the physiological processes behind this are not yet clear.

In summary, the relation between *BP* and *PAT* was not a simple one and thus, one could only show a weak correlation with general values, inverse values or differences. At the same time, the correlation between *HR* and *PAT* also showed that it depends on the situation. Thus, after a stress stimulus, certain CV parameters seem to be synchronised with each other. This suggest that CV parameters are regulated by a complex physiological control system [36] and many different parameters influence them.

5.7 Limitations

There are few limitations to this work. *BP* was not measured during the tasks, because on the one hand it could impair the patients and on the other hand the measurement signal would probably have been rich in artefacts. It would have been interesting to see how the *BP* data behaved in the task phases and to what extent it would influence the co-relationship between *BP* and *PAT*.

The task in this study was either climbing stairs as a physical task or performing a modified DemTect [75] test as a mental task. The times for each task were approximately five minutes. As many of the participants were elder and almost all had cardiovascular diseases or other medical conditions, some of the participants had to take breaks during

the physical task. Although these breaks were marked in the signals, nevertheless a change in cardiovascular parameters occurred when a break was taken. In some cases the time of the physical task was also longer or less than five minutes. The mental task generally took less time.
An unequal signal length affects the comparability of the values. Therefore, the HRV parameters were evaluated for the length of the shortest signal, which was about two minutes. Since HRV data are usually calculated from five minute signals or 24 hours signals and since the length of the signal also affects certain time parameters such as *SDNN* [62], it is difficult to compare the data of this study with literature values.

It was also not possible to use all participants data for the different CV parameters, as some were rich in artefacts, PPG signals were not always captured well and thus the peak and onset detection did not work or, as mentioned above, the participants also took breaks, began to sweat or some subjects suffered from tremor, and thus the signal quality decreased. The signals were measured with a hand-held device and the contact between the fingers and the sensors can loosen during movements, or the contact force in general can vary. This affects the pressure-volume characteristics of the artery [28] so the PPG signal could have been easily altered. If only those data sets, where all parameters were available, had been used, statistical analysis would have been impossible, so unfortunately the number of data sets for each parameter and for each group is different. This makes it difficult to compare the values, but only in this way, it was possible to carry out statistical tests.
Unfortunately, it was not possible to determine whether hypertensive subjects react longer to the mental or physical task, since all BP classes are mixed together in the mental and physical group. An exact allocation would not have been advisable, as there would have been too little data for the evaluation.

Another limitation are the normalized *CT*, *DT* and *NT* values. Because each pulse wave was normalized by one second, certain phenomena did not occur and the parameters cannot be compared with other studies that did not normalize their values. However, for the correction of *HR*, this normalization was performed. For the future, pulse waves could be normalized differently, i.e. by superimposing the individual waves per phase and taking the average of this superimposition, as shown in the study by Celka et al. [71].

6 Conclusion

This study investigated the progression of several cardiovascular parameters that were evaluated from 48 hypertensive subjects during resting states, a task phase and during a recovery state. The task was either a mental DemTect test or a physical one with climbing stairs. With the recorded ECG and PPG data *PAT*, *HR*, HRV data like *LF/HF*, *SDNN* and *RMSSD*, pulse wave characteristics such as the *CT*, *NT* and *DT* as well as *IPA*, and *sVRI* of the PPG signal were evaluated. Correlations between *BP* and *PAT* as well as correlations between *PAT* and *HR* were established with the intermittent recorded blood pressure data. Since there were different tasks, different age groups, different sexes and different blood pressure classes, the results were also divided among these groups.

In principle, during the task the activity of the SNS increased and the activity of the PNS decreased, which was reflected in an increase in *BP*, *HR*, *LF/HF* and a decrease in *RMSSD*, and *IPA*. However, as changes in parameters were expressed differently between the mental and physical task, it can be assumed that different mechanisms are involved in the cardiovascular response to a mental or physical task, or that other factors play a role.

The physical task elicited stronger responses than the mental task. However, despite an increase in *SBP*, *DBP* as well as an increase in *HR* during the mental task, there were no *PAT* changes. For HRV, an increase in *SDNN* and no change in *RMSSD* was observed, indicating that the mental task elicited mild HRV responses. However, in the recovery phase, PNS activity increased and SNS activity remained the same in the mental task and the opposite occurred after the physical one, i.e. SNS activity decreased and PNS activity remained the same.

The unchanged *PAT* data was also observed in male subjects, older subjects and subjects diagnosed with hypertension, giving reason to believe that these factors contribute to the interplay between *BP*, *PWV* and ultimately *PAT*. It could also be seen that hypertensives and subjects with elevated BP showed an increase in *LF/HF*s during the task but with an increased *SDNN* value suggesting resilience and increased HRV. However, they did not show any recovery after the task by increasing PNS activity, whereas normotensive ones did. In addition, hypertensives had a general increased arterial vascular tone, as *PAT* was lowest at the resting states and *IPA* did not recover after the task. A further increase in vascular tone did not seem to be an option here, which is why the cardiovascular reactions in the hypertensive subjects were also lighter.

Correlations between *SBP* and *PAT* were significant but insufficient to infer from one parameter to the other. Furthermore the high correlation between *HR* and *PAT* in the recovery state support also the assumption that more influencing factors are responsible

for the relationship between BP and PAT or PWV and the degree of changes behind the parameters.

Based on the data, it appears that the relationship between PAT or the underlying PWV with BP is not quite so trivial but in accordance with the literature it is related to the sex, age and cardiovascular risk factors.

6.1 Outlook

A limitation of this study was that the groups were not evenly distributed. The participants in this study were randomised, and could be stratified in the future. A possibility to deal with uneven groups would be a multivariate statistical analysis. With this method, it is possible to examine several influencing factors at the same time, but that would have gone beyond the scope of this work.

In order to see whether the different tasks are also perceived as stressful situations or their degree of stress, a questionnaire could be carried out in addition that identifies the perceived stress level, their coping skills or their ability to cope with stress. Those scores could then be compared with the determined cardiovascular parameters. Using the obtained stress scores and some of the continuous cardiovascular parameters, a model could be developed that can be used as a stress indicator. Since the device can be hand-held and the questionnaires can be answered before and after the task, there are various fields of applications.

Since it is also shown that the relationship between BP and PAT is not a simple linear one, the influencing factors should be investigated. Pulse wave characteristic data can provide useful data here, as it indicates pulse wave reflections, amplifications and attenuations, but it would be useful to calculate these data differently, so they can be better compared with literature and also with the physiological processes in the body.

Appendix

A.1 Mental Task

Durchführung DemTect (Gesamtzeit zur Lösung der Aufgaben 5 Min):

1) **Wortliste:**

folgende 10 Begriffe werden dem Patienten 1 x genannt

Begriff	Abfrage sofort	Erneute Abfrage (2)
Teller		
Hund		
Lampe		
Brief		
Apfel		
Hose		
Tisch		
Wiese		
Glas		
Baum		
Richtig erinnerte Begriffe		Max. 20

0 = nicht korrekt erinnert
1 = korrekt erinnert

2) **Zahlen-Umwandeln** modifiziert (Original schriftlich Zahl in Schrift / Schrift in Zahl)

Addieren der einzelnen Ziffern

Ziffern	Ergebnis	Punktzahl
2093	14	
40547	20	
Richtige Addition (max. 4 Punkte)		

Pat. Nr: Pat. ID: Datum:___/___/_____

3) Supermarktaufgabe (1 Min)

o o o o o o o o o o
o o o o o o o o o o
o o o o o o o o o o

genannte Begriffe (max. 30) _____

Zahlenfolge rückwärts

1. Versuch	**2. Versuch**	**Erreichte Punktzahl**
7 – 2	8 – 6	**2**
4 – 7 – 9	3 – 1 – 5	**3**
5 – 4 – 9 – 6	1 – 9 – 7 – 4	**4**
2 – 7 – 5 – 3 – 6	1 – 3 – 5 – 4 – 8	**5**
8 – 1 – 3 – 5 – 4 – 2	4 – 1 – 2 – 7 – 9 – 5	**6**
Längste richtig rückwärts wiederholte Zahlenfolge (max. 6)		

4) **Erneute Abfrage der Wortliste** (s. unter 1)

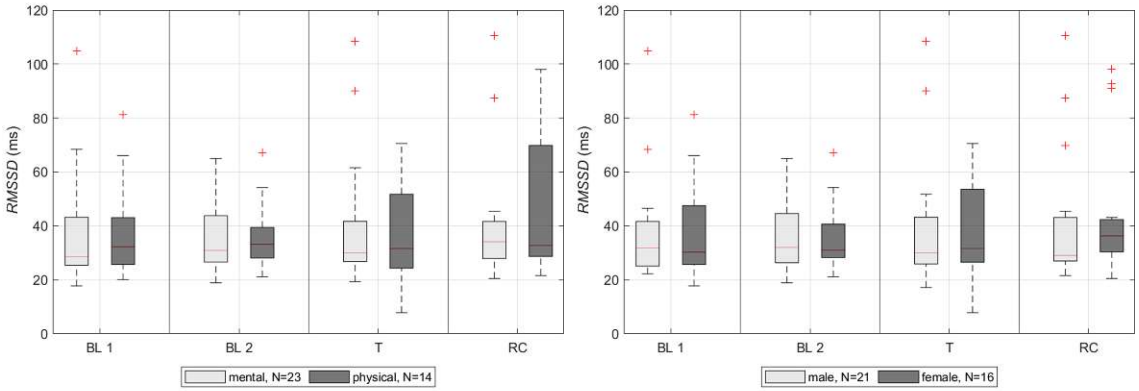
Begriff	Erneute Abfrage (3)
Teller	
Hund	
Lampe	
Brief	
Apfel	
Hose	
Tisch	
Wiese	
Glas	
Baum	
Richtig erinnerte Begriffe	Max. 10

0 = nicht korrekt erinnert
1 = korrekt erinnert

Pat. Nr: Pat. ID: Datum:___/___/_____

A.2 Additional Plots

A.2.1 Root Mean Square of Successive Normal-to-Normal Differences



(a) Group of mental task light grey and group of physical task dark grey.

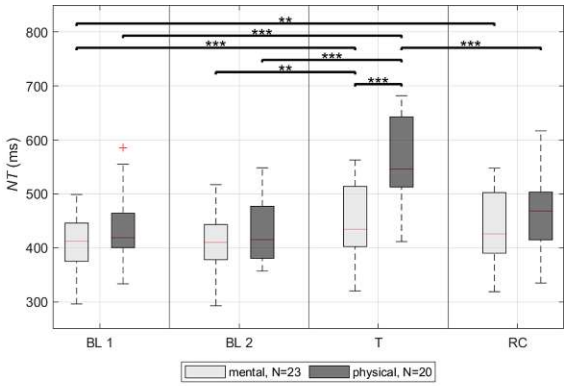
(b) Group of male light grey and group of female dark grey.

(c) Group of older participants light grey and group of younger ones dark grey.

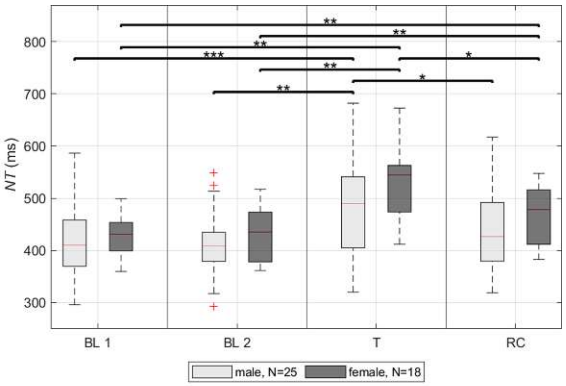
(d) Normal BP in light grey, elevated BP in middle grey and hypertension in dark grey.

Figure A.1: Grouped boxplots of *RMSSD*s (ms) during both baselines (BL1, BL2), during the task (T) and at the end (RC) for different groupings.

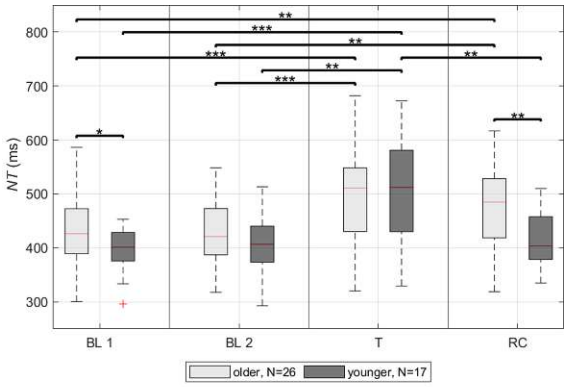
A.2.2 Notch Time



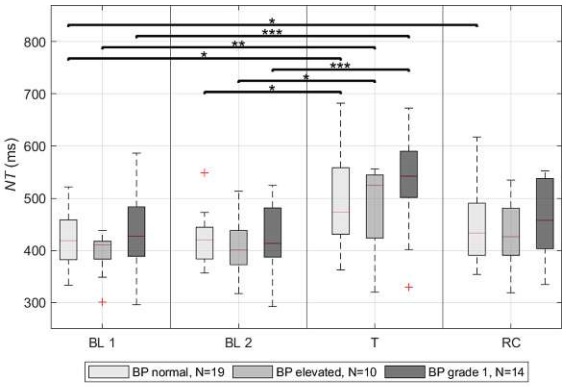
(a) Group of mental task light grey and group of physical task dark grey.



(b) Group of male light grey and group of female dark grey



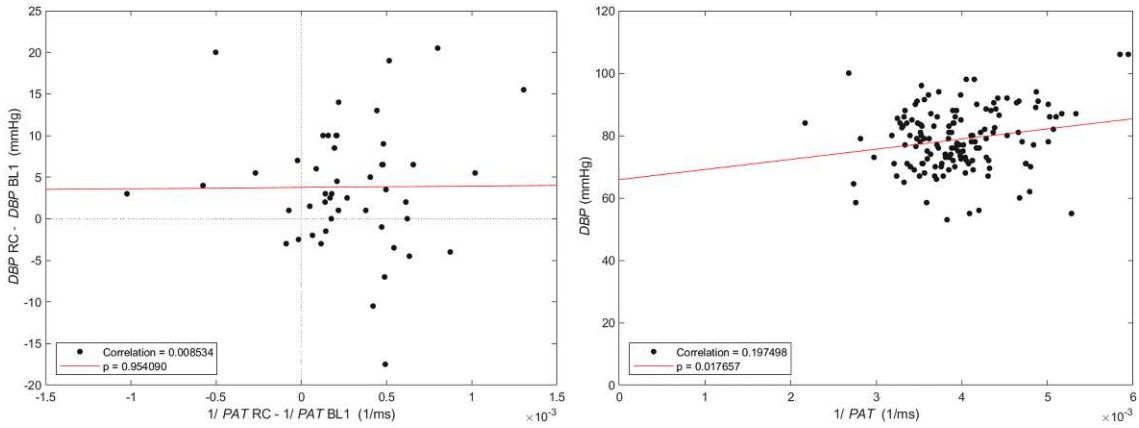
(c) Group of older participants light grey and group of younger ones dark grey.



(d) Normal BP in light grey, elevated BP in middle grey and hypertension in dark grey.

Figure A.2: Grouped boxplots of *NT*s (ms) during both baselines (BL1, BL2), during the task (T) and at the end (RC) for different groupings.

A.2.3 Correlation Diastolic Blood Pressure and inverse Pulse Arrival Time



(a) Correlation between *DBP* (mmHg) difference and inverse *PAT* (1/ms) differences.

(b) Correlation between *DBP* (mmHg) and inverse *PAT* (1/ms) values.

Figure A.3: (a): Correlation between *DBP* (mmHg) differences between recovery values and baseline values with the inverse *PAT* (1/ms) differences.
(b): Correlation between averaged *DBP* (mmHg) values in the first and second baseline and the recovery phase, with the inverse *PAT* (1/ms) values.

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