The History and use of Heart Rate Monitors in Human Factors: A Literature Review

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Abstract

This is a literature review exploring the history and development of heart rate monitoring (HRM) devices, starting from the beginning of time, to recent history. Then, some smart design considerations for the development of heart rate monitors are discussed. The use of heart rate monitoring devices is then discussed, detailing their use for different applications in the field of human factors. First, HRM's instrumentation in measuring mental workload will be discussed. Second, the HRM's usage measuring the user's general physical effort on a task is examined. Then, the HRM's use in measuring a user's affect in a human-computer interaction context is explored. The literature review concludes with a brief section imagining the future developments for HRMs and their future utility in the human factors field.

Keywords: heart rate monitor, HRM, human factors, medical human factors

The History and Use of Heart Rate Monitors in Human Factors: A Literature Review

Methods for assessing one's heart rate have existed for millennia, some more low tech than others. In fact, mere centuries ago, doctors would listen to a patient's heart rate and rhythm by simply placing their ear against the patient's chest (Achten and Jeukendrup, 2003). Today, the development of heart monitoring equipment progressed as far as wireless technology, letting the health care team know about the status of the patient without having to visit them in their room.

Heart rate monitors (HRM) are a category of device that is not just used in one application for one purpose—the HRM has a wide utility for a variety of applications. According to Achten and Jeukendrup (2003), heart rate monitors are used prominently in the exercise sciences and in recreational exercise for the typical home consumer. Users including both amateur and professional athletes measure their heart rate using personal wearable heart monitoring devices equipped with advanced features such as maximal oxygen uptake and calorie counting features to provide a guide for the intensity of their workouts. The application of heart rate monitors extends greatly beyond exercise—the field of human factors uses heart rate monitors as a method of collecting physiological data in field experiments. The applications for assessing heart rate ranges from assessing physical workload during a task to see if the individual is performing the task safely and efficiently, to evaluating products during the product lifecycle as a way to gauge affect. The field of medicine also use heart rate monitors for monitoring patient's heart health and are a main driving force in developments, along with the exercise sciences field, in the development of unobtrusive and precise heart monitors.

This literature review will examine the history and development of the heart rate monitor, usability and design considerations for developing HRMs, applications and instrumentation for the field of human factors, and future implications and developments for the device.

The History and Use of the Heart Rate Monitor (HRM)

While humans have known of the existence of the heart since the time of the Egyptians, where the heart is pictured on papyrus paper, being weighed by the god Anubis due to the Egyptian religious belief that the soul was the contained in the heart, and the ancient Greeks, who regarded the heart as the source of heat in the body, the heart's anatomy and physiology was mostly unknown until the 20^{th} century, save for the renaissance era's drawings of the heart by anatomists and artists after completing dissections (The University of Sydney, n.d.). In those times, the liver was understood to pump blood throughout the body in a centrifugal matter, and blood was understood to dissipate at the ends of veins and arteries, rather than circulate in a closed system (Aird, 2011). It was not until the 17^{th} century, in 1628, when the understanding of how the heart pumps blood throughout the body in a closed circulatory system was discovered by an English researcher named William Harvey (Aird, 2011). An understanding of cardiac electrophysiology, or how the heart functions through electrical activity contracting the heart muscle, was not discovered and understood completely until the work of Sunao Tawara in the early 1900s (Aird, 2011).

Diagnosing a person through their pulse has existed long before these times. In ancient Chinese and Indian medicine, approximate pulse rate and patterns have been measured qualitatively, through measuring the pulse through the tongue and wrist (Ernst, 2017). As time has gone on, the development of quantitative measures of pulse rate have been developed.

The first major development to heart monitoring technology was the invention of the stethoscope by René Laënnec in 1816 (Roguin, 2006). While the stethoscope is a far cry from the current technology available and depends on the operator's interpretation of heart sounds for accuracy, the technology that previously existed solely involved the health care worker placing their ear against the patient's chest. Laënnec, a physician, was too embarrassed to place his ear to his women patients' chests to assess their heart and lungs, so he developed a portable, partially dismantlable device (see Figure 1.) made of a hollow tube of wood fitted with a single ear plug, allowing physicians to listen to the heart and lungs (Roguin, 2006).

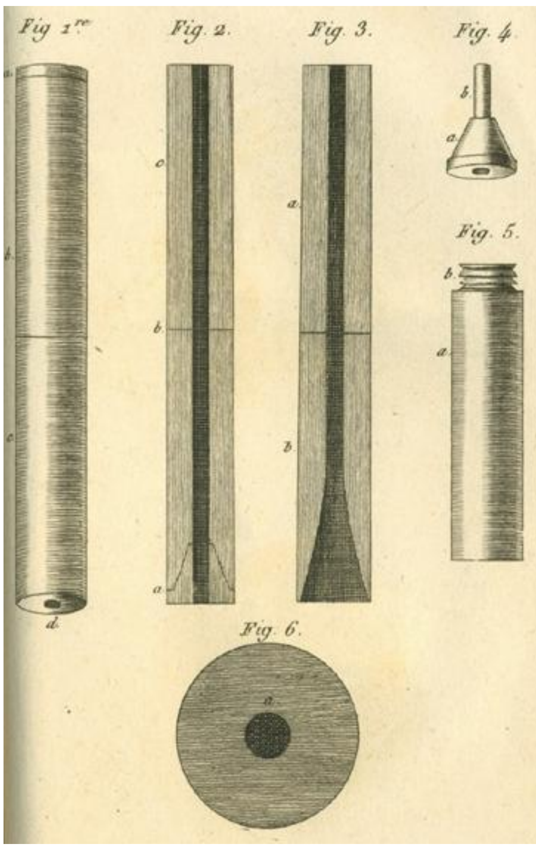

Figure 1. Laënnec's schematic for the first stethoscope (1819).

Since Laënnec's invention, the stethoscope evolved into a binaural device with a percussive chest piece and tubing, with some expensive models (such as the 3M™ Littman® M3200) now featuring an electronic chest piece equipped with sound amplification, ambient noise reduction, an LCD display, and Bluetooth for sound visualization and for collaborative telemedicine.

As our understanding of the heart's physiology, particularly the understanding of the electrical activity in the heart improved, scientists worked to develop devices that could measure this activity. The Electrocardiogram (ECG) was a term for the graphical output of cardiac electrical activity developed in 1895 by Willem Einthoven, ushering in a new era of cardiac and general medicine. The ECG provided users with information about the structure and function of the heart for clinical applications, which is still in use today. The first electrocardiograph developed by Einthoven, called the string galvanometer electrocardiograph weighed over 600 pounds and detected both cardiograph and electrometer information, which combined results in the ECG output (AlGhatrif & Lindsay, 2012). The sting galvanometer, while heavy and bulky, provided a more sensitive measure of heart activity than the capillary electrometers in use just decades prior (AlGhatrif & Lindsay, 2012). The device worked using five electrodes (placed in the four extremities and the mouth) and ten leads. The electrodes were not the peel and stick variety seen today; these electrodes were made up of cylinders filled with electrolyte solution in which the extremities of those being measured were submerged (refer to Figure 2).

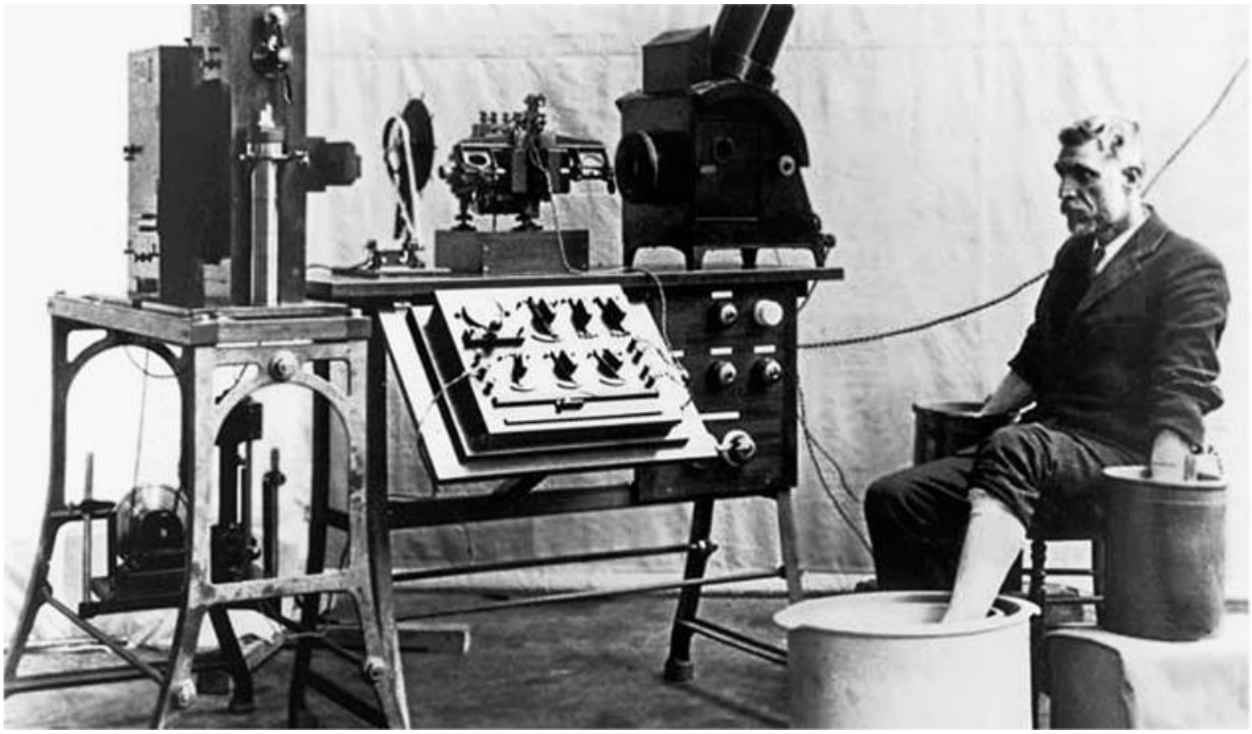

Figure 2. Einthoven's string galvanometer electrocardiograph, the first ECG machine.

The string galvanometer electrocardiograph became developed for clinical use, and redundant or low-yield leads were removed to increase the unobtrusiveness of the device, bringing the total leads to three. As more clinical sites adopted the device after World War I, more developments were made to replace the electrolyte solution with less intrusive electrodes, and the placement of the electrodes on the body were altered to the chest and back areas. The entire device was condensed down so that it could be rolled to the patient's bedside. By 1935, the electrocardiograph machine weighed only 25 pounds, further making the device accessible to hospitals (Rivera-Ruiz, Cajavilca, & Varon, 2008).

After World War II, scientists by the name of Himmelstein and Scheiner devised an electronic device capable of monitoring heart rate and rhythm called the cardiotachoscope. This device was novel because of the presence of a Cathode Ray Tube CRT monitor showing the ECG output, an indicator for measured heart rate, and an alarm system present for alerting the health care team when tachycardia (high heart rate, when resting beats per minute exceed 100bpm in adults) and bradycardia (low heart rate, resting BPM<60). Unfortunately, Himmelstein and Schiener's cardiotachoscope never reached the market, however, heart rate monitors, referred to as electrocardioscopes or cardioscopes were found in hospitals in the 1950s. During this era of heart rate monitoring devices, heart rate was not explicitly shown on the monitors; rather, these devices provided an audible beep and wave visualizations within a grid which allowed the physician to calculate the patient's heart rate (Rivera-Ruiz, Cajavilca, & Varon, 2008). This period of time also refined the design of the ECG machine with the addition of a spark proof enclosure for the device due to its use in the surgical space where flammable anesthetics were used (Femtosim Clinical, 2018).

In the 1960s and 1970s, the explosion of digital electronics propelled the ECG machine into a more portable and usable device. Waveforms and heart rate data were displayed on a monitor with a bigger screen, allowing the information to become more visible to the health care team using them (Femtosim Clinical, 2018). Another development on the hardware side was the addition of larger memory modules to the ECG machine, allowing short durations of ECG outputs to be stored and rewritten to the CRT screen, allowing for a persistent display. The output could also be paused by the operator, allowing them to study the waveform in a way which could not be achieved before (Femtosim Clinical, 2018).

While developments of heart rate monitoring devices improved the portability and unobtrusiveness of the devices, the developments in the wearable heart rate monitor we are familiar with today have only existed in the past 40 years, mostly driven by the athletic field's desire to use heart rate monitors as a training aid. The first wearable electronic heart rate monitor was developed by Polar Electronics in 1977 in Finland. This device, the Tunturi Pulsar (see

Figure 3) , was a finger monitor with a monitoring belt (the belt released later, in 1984) (Kite-Powell, 2016).

Figure 3. Polar Electronics' first fingertip heart rate monitor, the Tunturi Pulsar.

Later, in 1982, Polar released the first wire-free, wrist mounted wearable called the Sport Tester PE 2000 (Kite-Powell, 2016). Later developments of the wearable wrist mounted heart rate monitor in the 1980s and 1990s allowed the user to export their heart rate analysis to their personal computer. As for the wired ECG devices used in the clinical setting, their monitors now boasted color displays and the ability to display multiple waveforms at once due to the larger screen size and pixel density available. In the 1990s, the connectedness between different monitoring devices in a given hospital also increased with the development of a monitoring network. This connectedness increased nursing efficiency by enabling nurses to have the ability to enter a patient's data at the bedside monitor, rather than having them leave the patient's room to view their data on the centralized monitor (Femtosim Clinical, 2018).

In the new millennium, heart rate monitoring technology improved with the development and proliferation of the internet, which now allow internet-connected, wearable commercial heart rate monitors to constantly transmit data to a centralized app, where users can then export that data, along with information about their overall cardiac health for analysis by their health care team. The consumer market of wearable heart rate monitoring devices has extended from their niche use by athletes to track the efficacy of their training, to the average consumer with the release of the Apple Watch and Fitbit devices. Heart monitoring technology is now amalgamated with applications to view and send text messages from the watch without the user needing physical access to their phone, extending the utility and accelerating the ubiquity of HRMs in daily life. In the clinical setting, these developments have resulted in accurate, Bluetooth and internet-connected wireless ECG devices are used in hospitals to track a patient's cardiac activity, allowing the health care team to assess the patient's data and share that data amongst the team without even physically seeing the patient or entering their room through connecting these devices to the hospital's network (Aminian & Naji, 2013). The patient is still hooked up to the device through electrodes, but the monitoring device itself is small enough to slip into the pocket of the user's hospital gown for relatively uninterrupted ambulation (see Figure 4.).

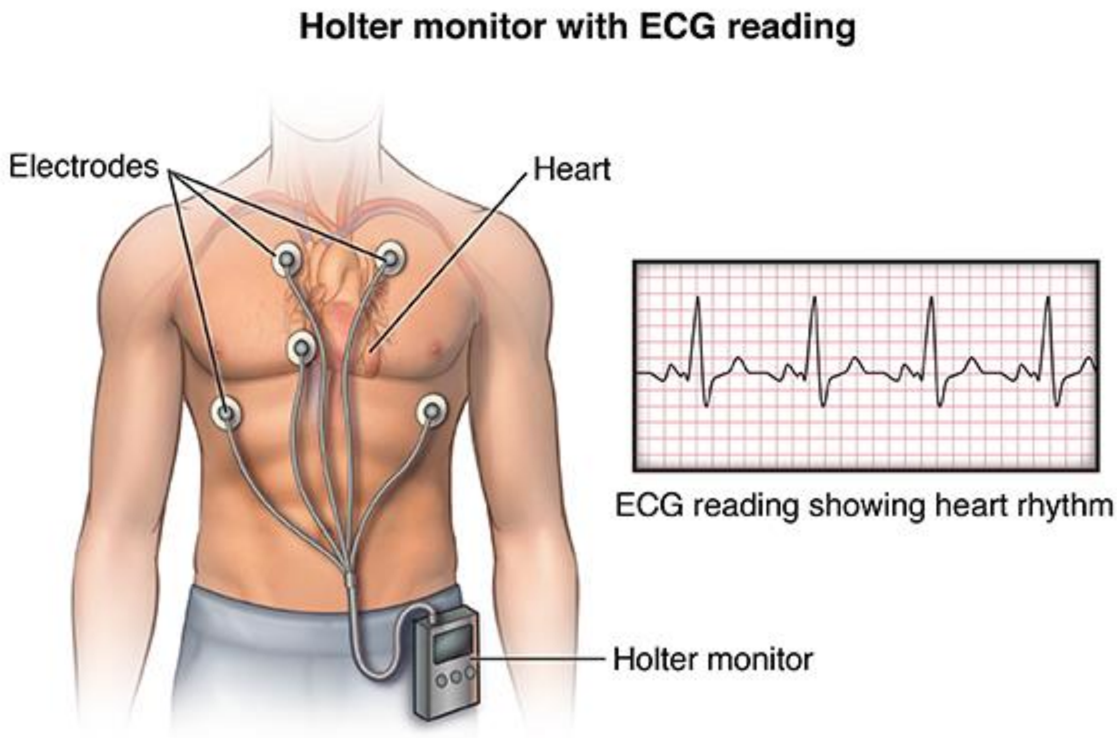

Figure 4. A portable ECG machine commonly used in hospitals today.

Limitations of using heart rate monitors depends on the type of technology being utilized. While most heart rate monitors use the ECG technology discussed previously, some modern wearable tracking devices use PPG technology. PPG, or photoplethysmography, uses beams of light and a sensor on the back of the device to detect changes in the blood volume passing through the veins of the wrist, which is then picked up by the device's optical sensor to produce a Photoplethtysmogram (PPG) reading, which is then analyzed by the device's software to estimate the user's current heart rate (Isakade & Martin, 2019). Certain devices, like Apple Incorporated's Apple Watch use a proprietary algorithm to analyze the tachogram, or the graphical depiction of the movement and rate of blood flow in the wrist using PPG technology (Isakade & Martin, 2019).

The EGC devices seen in hospitals use multiple leads and electrodes to accurately measure a person's heart rate and rhythm. Some of the latest wearable heart rate monitors for the consumer market use a single lead in their electrocardiogram (also known as iECG technology). The iECG technology works through completing an electrical circuit between the detector plate on the back of the iECG enabled device and the bezel of the device through the user placing their finger(s) on the bezel (Isakade & Martin, 2019). This allows a completely wireless and relatively unobtrusive measurement of the user's sinus rhythm after about 30 seconds.

For both ECG and PPG wearable technology, the accuracy is highest when the user is at rest, where artifacts introduced from moving the arm are reduced (Isakade & Martin, 2019). For devices using PPG technology, Preejith, Jayaraj, and Sivaprakasam (2016) found that users with a dark skin tone or dry skin showed a slight deviation in their heart rate reported from the device from the true measurement of their heart rate gained through ECG data. In addition, the ECG on a consumer fitness product and the ECG differs through the amount of leads present on the body. While iECG-enabled devices use only one lead, and thus one picture or point of information about heart health, an ECG used in hospital uses up to 12 leads, providing a more accurate picture of the status of the heart through multiple channels of data (Isakade & Martin, 2019). In addition, issues of false positive and negative reading using wearable heart rate monitors have been identified. HRMs used in medical applications utilize advanced machine learning in their algorithms for interpreting the ECG and PPG data coming in from the multiple sensors, while HRMs in personal devices use technology and software that is not as accurate, thus heart rate measures gathered from consumer devices should be used as a guide to heart function only, and results should not be held as the "gold standard", compared to medical HRMs (Sawh, 2020).

Because the heart rate monitor has had many developments in the past few centuries, allowing for a more accurate and precise measurement of a user's cardiac activity, many fields have utilized the measure of heart rate as a quantitative measurement for multiple factors, including the field of human factors. The following section will discuss some general design considerations for heart rate monitoring devices.

The Heart Rate Monitor's Design Considerations

There are human factors considerations for the design of a heart rate monitoring device. These considerations do not only hold true for the field of human factors but are general usability criteria for all applications of these devices. Field experiments in certain domains like workplace safety and experiments involving the military may require more stringent requirements for these devices to meet their standards for usability. A standard 12-lead ECG machine may not be usable for a field experiment involving a high degree of movement; therefore, the real-world application of a particular heart rate monitoring device should be considered when designing them.

First, the HRM must be able to consistently and accurately measure the value that the device is developed to measure (Montes, 2019). For example, if the HRM is solely responsible for measuring heart rate, it should be assumed that this device, should it be usable, measure heart rate accurately and be precise in its HR measurements each time. If heart rate variability (HRV) is of interest, then the device should be expected to precisely and accurately analyze and report HRV.

Montes (2019) further explained that the HRM should be able to provide these accurate and precise measurements across multiple environments and conditions. For example, a heart rate monitor should be able to still provide accurate measurements for an operator's HR in a field condition where excessive perspiration and dirt may exist. In some human factors field experiments, especially those involving measuring pilots' heart rate, G-forces may be introduced and the HRM must respond accordingly.

In addition, because human beings have individual differences in a multitude of areas such as weight, height, age, and muscularity, the heart rate monitoring device must also be validated for those persons who fit on the extreme ends of the normal body characteristics (Montes, 2019). Designers of these heart rate monitoring devices should consider users who are elderly, who are overweight, who are tall, who have wider wrists or a wider chest than average so that the device can have a wider utility. These individual factors will also affect the measure of the user's measure of heart rate variability (HRV), discussed later in this text.

A fourth consideration for the design of a heart rate monitor is that the device should be financially feasible to purchase (Montes, 2019). For example, the Apple Watch, while having a proprietary and relatively accurate heart rate measure compared to other consumer devices currently on the market, is not as available to those of a lower socioeconomic status than those of a higher socioeconomic status. In a similar vein, an entity interested in studying mental workload may not be able to afford a certain device for their research.

A fifth consideration for the design of heart rate monitors is that while worn, the device should be unobtrusive to the user (Montes, 2019). Having multiple wires hanging from the device may impede the user's movement and may influence measurements by altering the user's gait and arm movement.

A sixth design consideration is that the device is safe for the user to operate. In the surgical space, flammable substances are spread throughout the room, potentially causing a fire hazard or explosion if a spark occurs. Intelligent design of heart monitoring devices keep in mind the environments the device will be used in to prevent user harm and damage to property surrounding the operating environment. In addition, Montes (2019) suggested that the materials the device is made out of are non-toxic to the user and comfortable to wear and operate, especially if the heart rate monitoring device is intended to be used for long periods of time.

The seventh and final design consideration for heart rate monitors is that the device must be user friendly and not overly complicated to use (Montes, 2019). The usability side of design has a wide breadth of topics. For example, design considerations for the controls and displays of a heart rate monitor can be a completely separate manuscript spanning hundreds of pages long. This document will explain some of these usability considerations.

As for the display of the heart rate monitoring device, there should be no clutter and the measure of the estimated BPM and the waveform of the person of interest's sinus rhythm should be clearly displayed (if the display shows waveforms). This usability consideration has implications in an emergency situation, where the person trying to read the patient's analysis must be able to have their eye drawn to the relevant data quickly, without having their visual search task inundated with clutter. Colors used for the waveform and HR reading should be stark against the background of the rest of the display, can be used to link objects on the display together if the same colors are used for those objects, and not use any warm and cool colors together (like red/green and red/blue), which results in operator eye fatigue and discomfort (Wickens, Lee, Liu & Gordon Becker, 2004). In addition to color, objects on the monitor display that are related to each other may also be linked together through close proximity, demonstrating the proximity compatibility principle, where mentally integrated tasks should be represented on the display in close proximity to each other, while mentally separated tasks should be represented further apart (Wickens et al., 2004). The alerting system of the HRM, especially if used in a clinical environment, must also use an omnidirectional auditory channel for alerting critical abnormal heart rate measures, along with flashing lights to capture users' attention, while less critical abnormalities should be represented by less salient auditory alarms and, in least critical situations, advisories can be purely visual in nature (Wickens et al., 2004). In an emergency situation or field experiment, where accessing pertinent information on the display is critical for a good outcome for the patient or study, careful consideration of usability criteria is important. A consumer device needs to consider "user-friendliness" even more because the user is not a trained professional; the user may be someone with a wide variety of skills and education.

The following section will discuss the utility of HRMs in the human factors field, as well as implications and limitations of using HRMs during human factors field experiments.

The Heart Rate Monitor's Utility in Human Factors

The field of human factors use heart rate monitors for a breadth of different applications, mostly to gather data on physiological indices of certain subjective and objective phenomena. Gathering heart rate data is the easiest information gathered from an ECG output (Kramer, 1990).

In their article, Xiao, Wanyan, and Zhung (2015). defined mental workload as, "the functional relationship between the mental resources demanded by a task and the available mental resources provided by the operator". Current human factors researchers measure mental workload through administering instruments like the NASA-TLX (a subjective questionnaire developed by NASA involving six seven-point Likert scales), measuring the operator's performance on the task (accuracy), and using physiologic measures like eye tracking technology, where the measurement of factors such as blink frequency and fixation time are studied, and heart rate.

Before the 1980's, the user's heart rate data was of interest to human factors professionals in their study of human information processing and mental workload. Unfortunately, an issue with solely studying a user's heart rate arose through inconsistent findings in field experiments studying the relationship between heart rate and mental workload (Kramer, 1990). These inconsistent findings could be explained through Lacey and Lacey's work in the 1960s and late 1970s. In their manuscript, they described the intake rejection hypothesis, which suggests that the directionality of heart rate change is actually related to the type of tasks demands placed on the user (Lacey, 1967). The user's heart rate is proposed to decrease during the intake of environmental information, such as in visual detection and discrimination, scanning, and listening, and the heart rate is proposed to increase during the rejection of environmental information, such as during mental arithmetic, mental rotation tasks, memory retrieval, and problem solving situations (Kramer, 1990). Thus, the studies finding inconsistencies involving the relationship between mental workload and heart rate propelled the field to find other measures for assessing mental workload.

In the field of human factors, a person's heart rate variability (HRV) is used as one of the methods to assess mental workload. Heart rate variability is calculated from the continuous monitoring of the person's heart rate using a heart rate monitoring device. HRV is a measure of the fluctuation of the interval between consecutive heartbeats (Rowe, Silbert & Irwin, 1998). HRV can be measured over shorter periods of time (around five to ten minutes) or longer periods of time (around 12 to 24 hours) (Ernst, 2017). Additionally, HRV is measured in milliseconds. There are multiple ways to obtain a value of HRV: time domain measures allow the researcher to calculate scores like standard deviation or number of successive waves from inter-beat intervals, but disallows insight into reasons for variability in the HRV value (Jorna, 1992). Additionally, Jorna explains that statistical calculations can be conducted to show different properties of the signal from the ECG or other heart rate monitor (1992).

Spectral analysis of the analog signals is the preferred method for obtaining HRV measures. A Spectral analysis shows a total frequency content from three distinct frequency components. If the method for gathering this data is not continuous, there must be additional processing of the output through interpolation or low-pass filtering (Jorna, 1992). The first frequency, a low frequency (0.02-0.06 Hz range), mainly originates from body temperature (Jorna, 1992). The second frequency, a mid-frequency (0.07-0.14), relates to oscillations representing the short-term regulation of blood pressure (Jorna, 1992). The third frequency, the high-frequency (0.10-0.50), represents respiratory influences on heart rate, also called respiratory sinus-arrhythmia (Jorna, 1992).

HRV is a measure often used in human factors as one of the physiological measures of mental workload because according to Rowe, Silbert, and Irwin (1998), HRV measurements are relatively unobtrusive to the user, requiring only electrodes and a few combined leads being placed on the chest in ECG devices (the leads can be strategically combined and routed out of the way of movement), or by simply wearing the HRM device on the wrist for PPG devices. In addition, using heart rate as a physiological measure is advantageous because this provides a measure which do not require over performance by the user, meaning in the absence overt, observable physical behavior, heart rate data is still collected (Rowe et al., 1998). Of course, collecting data on both the overt performance of the user and the more covert physiological measures are most helpful, but the multidimensionality of physiological measures, including heart rate and heart rate variability provides multiple angles for viewing the user’s mental workload (Rowe et al., 1998). The author further explains that, because heart rate and heart rate variability are measured continuously, without interruption, this allows for these measures to provide a measure which responds quickly to the introduction of shifts in mental effort and workload. Research may also include measures of a user's heart rate variability (along with other physiological measures such as eye blinks, visual scan path, and accommodation) to evaluate many applications of mental workload, including evaluating display quality (Jacko, 2012).

When human factors professionals began exploring the relationship between heart rate variability and mental workload, they found that studies which previously discovered insignificant heart rate changes with the introduction of tasks of various workload, discovered large changes in HRV (Kramer, 1998). In general, a person's heart rate increases and HRV decreases during high levels of mental processing (Mulder, 1992).

HRV have been extensively explored through numerous human factors studies involving mental workload. A researcher by the name of Eilebrecht studied the relationship between a driver's mental workload and their heart rate variability though ECG data, finding consistency between a higher heart rate variability during a high load task during both a real-world driving experience, and a computerized simulation, compared to a low load task. (Guo, Tian, Tan, Li Wang, 2016). A study by Lo, Sehic, and Meijer (2017) explored the measurement of the mental workload of air traffic controllers in a training simulator using a variety of wearable heart monitoring sensors, finding that most of these sensors (with the exception of one) provided accurate HRV measures. A literature review written by Meshkati (1988) described multiple studies involving HRV and mental workload, including a study by Rault (1976) which examined pilots' HRV on an instrument landing procedure simulation task of varying difficulty, where the mean values of HRV varies with the programmed difficulty of the task, and a study by Hacker et al. (1978), which reported that helicopter pilots' heart rate increased during flight operations without an increase in oxygen consumption, suggesting the increase in heartbeat accounts for psychological activation.

A user's physical effort is also assessed through heart rate measures. In general, as a person's physical effort increases, the person's heart rate will also rise. Measures of heart rate variable may be useful for human factors research addressing workplace and task safety and efficiency. According to Bassett (2000), there is a linear relationship between a person's heart rate and their oxygen uptake (VO_2) over different exercise intensities, allowing the researcher to validate both against each other in an empirical study of exercise or intense physical activity. Freedson and Miller (2000) describes a few ways to analyze data from heart rate measures to estimate the amount of time performing physical activity of varying intensities. First, researchers can determine the amount of physical activity a person has completed by determining the number of minutes above a certain percentage of maximal heart rate, or heart rate reserve. Heart rate reserve is an attractive measure for researchers to use because this allows for the comparisons of people with different physical fitness levels (Freedson & Miller, 2000). Another method used to quantify activity is net heart rate, or heart rate under activity, minus baseline heart rate. While the net heart rate method also allows for the comparison of activity between individuals, this method does not allow for the estimation of total energy expenditure (Freedson & Miller, 2000). A third method of using heart rate to assess physical effort is called FLEX HR. This method involves measuring both the participant's heart rate and oxygen consumption while sitting, laying down, standing, and performing tasks at varying intensities (Freedson & Miller, 2000). Resting metabolic rate is also often obtained. The data gathered is then put into a heart rate/oxygen consumption curve, where a FLEX HR is calculated by the average of the highest HR from the sedentary activity and the lowest HR from light physical activity (Freedson & Miller, 2000). If a given heart rate is above the FLEX HR, the curve generated is used to estimate the participant's energy expenditure, while if a given heart rate is below the FLEX HR calculated, the measurement of resting metabolic rate is used to estimate energy expenditure (Freedson & Miller, 2000). Limitations of the FLEX HR method is that it is both costly and time consuming. Heart rate is a measure that may be influenced through multiple confounding factors (discussed later), so it is recommended to use heart rate along with another physiological measure to help make a stronger researcher design.

A user's affect can also be measured physiologically through their heart rate. According to Wilson, affect, from a psychological standpoint, refers to an emotion or subjective feeling (Jacko, 2012). Jorna (1992) explains that using heart rate can be useful from a psychological viewpoint as an indicator of change in the energetic state of the user as a function of psychological manipulations involving the difficulty of a task or introducing more time pressure. Changes in heart rate variability may also give cues into activation of the sympathetic nervous system, giving researchers insight to anxiety associated with a task or interaction with a system or product. Measuring a user's affect may be of interest to those studying the interaction between the user and a product. Noninvasive heart rate measures, like the fingertip pulse oximeter, may be useful for studying a user's affect. Heart rate may rise when a user is excited or thrilled while interacting with a product, demonstrating a positive affect toward the product or when they are frustrated with the product (negative affect). The variability in what a rise in heart rate could mean from an affect standpoint necessitates the use of more than one physiological measure of affect, or combining the physiological data with subjective measurements like an interview or questionnaire, or the observation of overt behavior. Some other physiological measurements of affect include galvanic skin response, respiration rate, readings from an electromyogram, and measurements of the user's blood pressure (Jacko, 2012). Balters and Steinert (2015) explain that only measuring pulse or analyzing ECG alone is not sufficient enough to gain insight into a subject's affect; instead these measures of heart activity should be used along with, for example, blood pressure readings (which gives insight into activation of the sympathetic nervous system through a rise in blood pressure from baseline readings, or insight into the activation of the parasympathetic nervous system through a fall in BP readings from baseline) to get a more accurate physiological measure of affect. In addition, Brosschot and Thayer (2003) found that negative emotions may last longer physiologically through prolonged cardiovascular activation, than positive emotions.

While using HRV and other heart-related measures in an experimental study, certain factors may affect the reliability and validity of your results. Jorna (1992), explains six different factors affecting HRV data.

First, respiration affects HRV data. Speaking while conducting a spectral analysis shows a larger range of higher-frequencies present than if the user was not speaking, making it difficult for researchers to analyze and interpret the user's heart rate spectrum (Jorna, 1992). Similarly, coughing, sighing, and other Valsalva movements should be minimized while measuring HRV.

Second, muscle activity can influence HRV (Jorna, 1992). Any exercise can increase HRV because of fluctuations in blood pressure and in breathing when trying to interpret a spectral analysis, so if the researcher does not intend to make physical differences in the tasks a participant must complete, those participants HRV will be affected.

In addition to activity, body position will also influence HRV. Standing in an upright position increases a person's HRV compared to the supine position, so researchers should be cognizant of body positions participants are placed in during their experiments (Jorna, 1992).

The physical fitness of a person also affects HRV. Generally, physical fitness lowers heart rate and increases the power of the spectra during a spectral analysis (Jorna, 1992). Therefore, aerobic fitness in participants should be controlled in a potential study.

The physical environment a HRV measure is taken in is also a factor. High ambient temperature and high humidity increases a person's heart rate and may affect HRV as well (Freedson & Miller, 2000). Researchers need to control these factors

Lastly, age is a factor which affects HRV. As a person advances in age, HRV can decrease (Jorna, 1992). The author further explains that many past field experiments confound a participant's experience and skill level with age, so absolute comparisons should be made withing one age group (1992).

Future Considerations for Use and Implications

Technology for heart rate monitoring devices is constantly improving, both in precision and accuracy. The validity and reliability of heart rate monitors' measure falter during high amounts of movement and activity, so there are devices being tested which combines heart rate PPG technology with a motion sensor to form a valid method for assessing total physical activity expenditure (Assaah, Ekelund, Brage, Wright, Mbanya & Wareham, 2011). In the future, heart rate monitors are predicted to get even smaller in form factor, facilitating ubiquitous computing, or computing in which users of this technology are not aware of and can seamlessly manipulate data without becoming cognizant of the technology driving these manipulations. Measuring heart rate may become almost completely unobtrusive to users, allowing researchers to gain a picture of the user's cardiac activation without the participant being encumbered by wires or without disruptions in task performance. While heart rate is usually used alongside other physiological measures in human factors field experiments, a user's heart rate data will likely never be replaced by another measure in the near future.

References

Achten, J., & Jeukendrup, A. E. (2003). Heart rate monitoring. *Sports medicine*, *33*(7), 517-538.

AlGhatrif, M., & Lindsay, J. (2012). A brief review: history to understand fundamentals of electrocardiography. *Journal of community hospital internal medicine perspectives*, 2(1), 10.3402/jchimp.v2i1.14383. https://doi.org/10.3402/jchimp.v2i1.14383

Aminian, M., & Naji, H. R. (2013). A hospital healthcare monitoring system using wireless sensor networks. *J. Health Med. Inform*, *4*(02), 121.

Assah, F. K., Ekelund, U., Brage, S., Wright, A., Mbanya, J. C., & Wareham, N. J. (2011). Accuracy and validity of a combined heart rate and motion sensor for the measurement of free-living physical activity energy expenditure in adults in Cameroon. *International journal of epidemiology*, *40*(1), 112-120.

Balters, S., & Steinert, M. (2017). Capturing emotion reactivity through physiology measurement as a foundation for affective engineering in engineering design science and engineering practices. *Journal of Intelligent Manufacturing*, *28*(7), 1585-1607.

Bassett Jr, D. R. (2000). Validity and reliability issues in objective monitoring of physical activity. *Research quarterly for exercise and sport*, *71*(sup2), 30-36.

Brosschot, J. F., & Thayer, J. F. (2003). Heart rate response is longer after negative emotions than after positive emotions. *International journal of psychophysiology*, *50*(3), 181-187.

Elliott, R. (1972). The significance of heart rate for behavior: a critique of Lacey's hypothesis.

Femtosim Clinical Inc. (2018, June 6). Fifty Years of Physiologic Monitors. Retrieved from http://www.femtosimclinical.com/History%20of%20Physiologic%20Monitors.htm

Freedson, P. S., & Miller, K. (2000). Objective monitoring of physical activity using motion sensors and heart rate. *Research quarterly for exercise and sport*, *71*(sup2), 21-29.

Hacker, W., Plath, H.E., Richter, P. and Zimmer, K. (1978). Internal representation of task structure and mental load of' work: Approaches and methods of assessment. *Ergonomics*. 21 (3), 187-194.

Isakadze, N., & Martin, S. S. (2019). How useful is the smartwatch ECG?. *Trends in cardiovascular medicine*.

Jacko, J. A. (2012). *The human-computer interaction handbook: Fundamentals, evolving technologies, and emerging applications*. Boca Raton, FL: CRC Press.

Jorna, P. G. (1992). Spectral analysis of heart rate and psychological state: A review of its validity as a workload index. *Biological psychology*, *34*(2-3), 237-257.

Kite-Powell, J. (2016, March 1). Polar: The Original Fitness Tracker And Heart Rate Monitor. Retrieved from https://www.forbes.com/sites/jenniferhicks/2016/02/28/polar-the-original-fitness-tracker-and-heart-rate-monitor/#6f7c0a205fe9

Kramer, A. F. (1991). Physiological metrics of mental workload: A review of recent progress. *Multiple-task performance*, 279-328.

Lacey, J. I. (1967). Somatic response patterning and stress: Some revisions of activation theory. *Psychological stress: Issues in research*, 14-37.

Meshkati, N. (1988). Heart rate variability and mental workload assessment. In *Advances in psychology* (Vol. 52, pp. 101-115). North-Holland.

Mulder, L. J. M. (1992). Measurement and analysis methods of heart rate and respiration for use in applied environments. *Biological psychology*, *34*(2-3), 205-236.

Preejith, S. P., Alex, A., Joseph, J., & Sivaprakasam, M. (2016, May). Design, development and clinical validation of a wrist-based optical heart rate monitor. In *2016 IEEE International Symposium on Medical Measurements and Applications (MeMeA)* (pp. 1-6). IEEE

Rault, A. (1979). Measurement of pilot workload. In N. Moray (Ed.), *Mental Workload: Its Theory and Measurement*. New York: Plenum Press, 4 17- 422.

Rivera-Ruiz, M., Cajavilca, C., & Varon, J. (2008). Einthoven's string galvanometer: the first electrocardiograph. *Texas Heart Institute journal*, 35(2), 174–178.

Roguin A. Rene Theophile Hyacinthe Laënnec (1781-1826): the man behind the stethoscope. *Clin Med Res*. 2006;4(3):230-235. doi:10.3121/cmr.4.3.230.

Sawh, M. (2020, January 10). ECG wearables: How they work and the best on the market. Retrieved May 05, 2020, from https://www.wareable.com/health-and-wellbeing/ecg-heart-rate-monitor-watch-guide-6508

The University of Sydney. (n.d.). Retrieved May 05, 2020, from https://www.sydney.edu.au/medicine/museum/mwmuseum/index.php/Anatomy_of_the_Heart

Wickens, C. D., Gordon, S. E., & Liu, Y. (2004). *An introduction to human factors engineering*. Upper Saddle River, NJ: Pearson Prentice Hall.

Xiao, X., Wanyan, X., & Zhuang, D. (2015). Mental workload prediction based on attentional resource allocation and information processing. *Bio-medical materials and engineering*, *26*(s1), S871-S879.

Appendix A

Figures Used in this Document

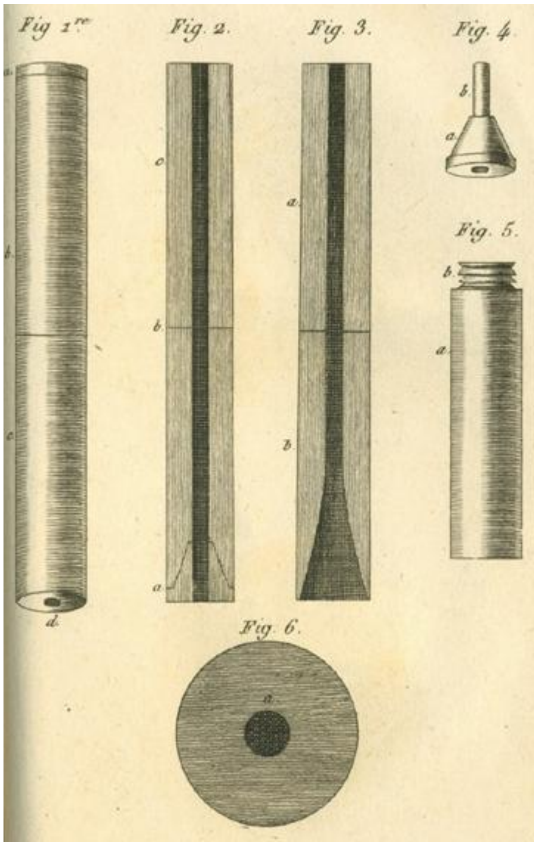

Figure 1. Laënnec’s schematic for the first stethoscope (1819).

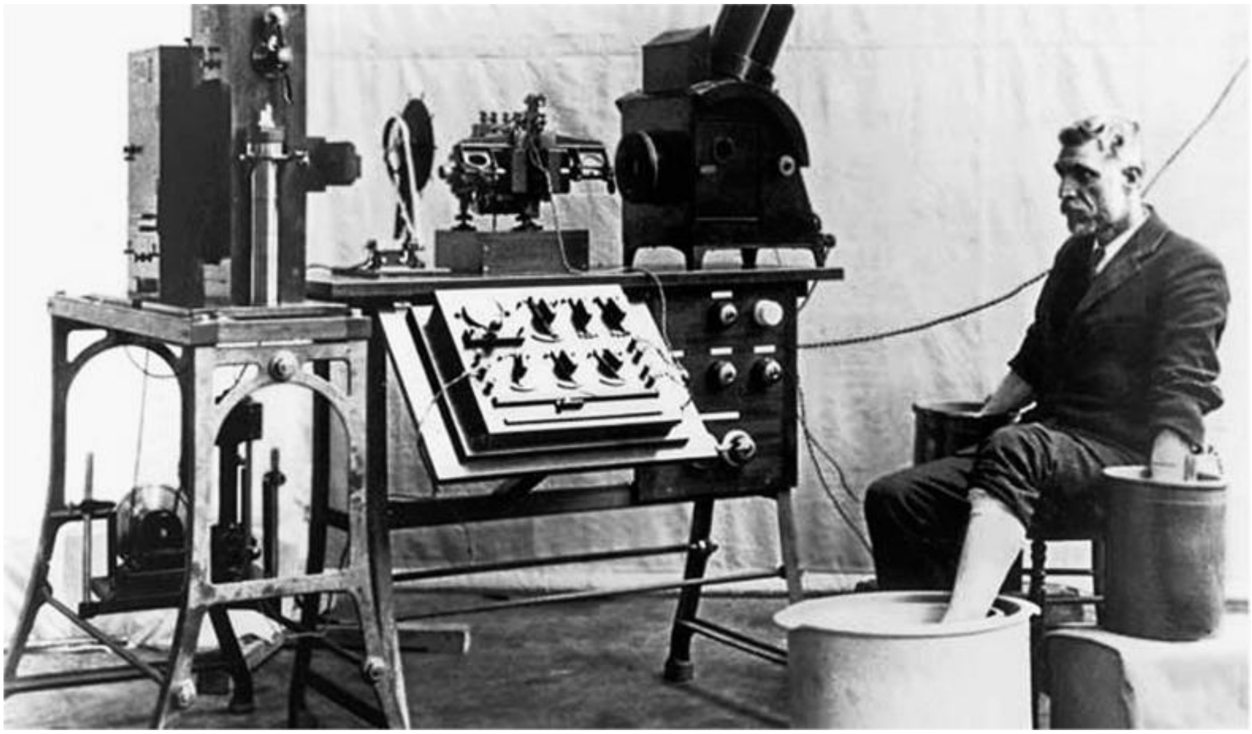

Figure 2. Einthoven's string galvanometer electrocardiograph, the first ECG machine.

Figure 3. Polar Electronics' first fingertip heart rate monitor, the Tunturi Pulsar.

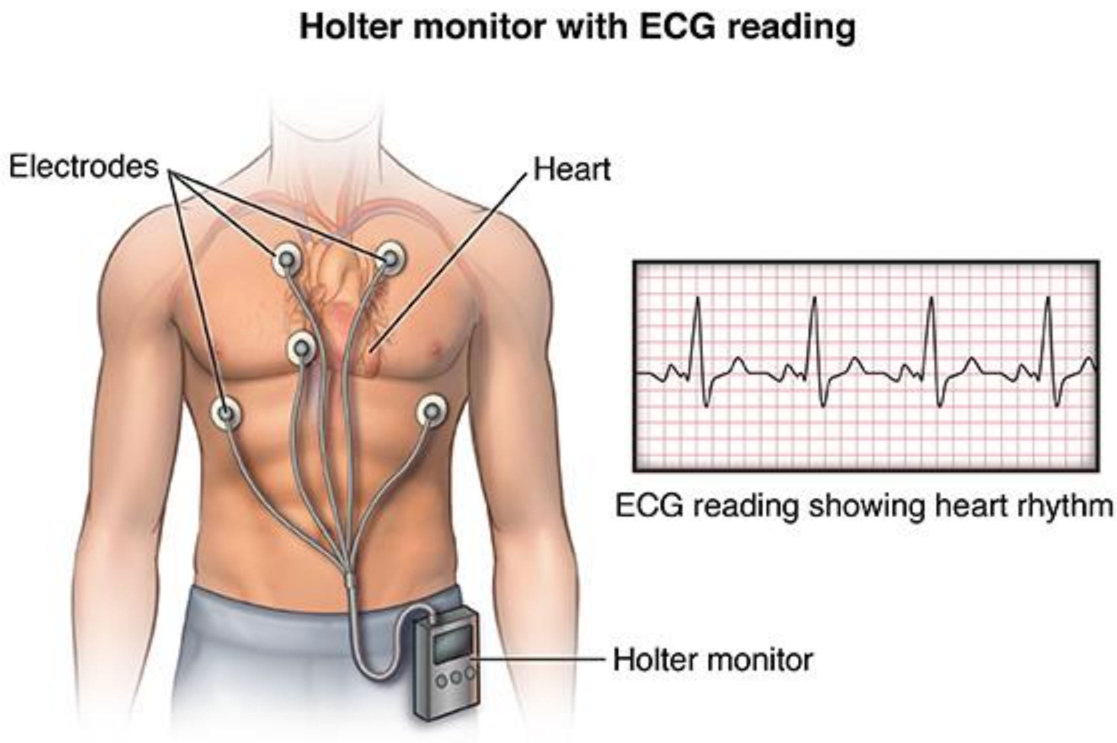

Figure 4. A portable ECG machine commonly used in hospitals today.