Heart rate and daily stress:
Examining the intra-individual correlation of heart rate and self-reported stress in low- and high-stressed adults

Emily K. Frye

University of Twente
Faculty of Behavioural, Management, and Social Sciences

St. No.: 1682695
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1st Supervisor: Matthijs Noordzij
2nd Supervisor: Youri Derks

UNIVERSITY OF TWENTE.

Abstract

Affective wearables, devices that can be worn on the body which measure physiological parameters, make use of an alleged correlation between heart rate and mental stress. This correlation, however, has only been investigated between-person. The aim of the present study is to investigate whether heart rate serves as a reliable indicator of mental stress, between- as well as within-person (intra-individually). Furthermore, it is investigated whether this correlation differs between low- and high-stressed people. Of in total 35 participants, HR and self-reported stress were obtained during their everyday life over the course of one week. The sample was split into a high- and a low-stress group. Only three participant showed a significant intra-individual correlation. The intra-individual correlations did not show any pattern within the groups (e.g. mainly positive or negative). The inter-individual correlations of the two variables per group were not significant, although the high-stress group had a moderate negative correlation of HR and perceived stress, whereas the low-stress group had a slightly positive one. Furthermore, the level of stress was not found to be moderating the association between herat rate and experienced stress. It is to conclude that HR is not a reliable indicator of experienced stress and therefore must not be used to assess a person's current stress level. The practical transferability of these findings is given due to the closeness to reality of the measurements and the subjective self-assessment of stress.

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Introduction

’Wearables’, such as smart watches or fitness bands that measure physiological parameters such as HR, blood flow, muscle activity and skin conductance become steadily more integrated into daily life. By reference to these parameters, people get to know more about their physical state and simultaneously draw inferences about their psychological state; emotions, arousal and - here particularly important - their stress level (Piwek, Ellis, Andrews, & Joinson, 2016). As a reaction to the growing demand for monitoring one’s inner state, these devices have been further developed. One of those more sophisticated devices are the affective wearables, which not only measure physiological parameters but additionally interpret the incoming signals as being indicators of psychological states such as happiness, anger and stress. The users therefore directly get informed about their alleged state of mind, often with the intention of becoming more aware of it, or being able to influence it (Hassib, Khamis, Schneegass, Shirazi, & Alt, 2016; Picard & Healey, 1997). The aim of the present study was to investigate the individual, as well as between-person association between heart rate (HR) and the amount of experienced stress obtained in intervals of two hours. While examining this association it was post-hoc distinguished between participants with a low and a high stress level, in order to explore the impact of constant stress on the HR. This is a follow-up study for Krüger’s (2018) investigation of the correlation between physiological and psychological parameters.

Apart from its psychological component, studies have shown the various physiological correlates of mental stress, such as hormonal change, increased muscle tension and cardiovascular changes, which are innervated by the autonomic nervous system. Within this nervous system an increased activity of the sympathetic nervous system, being activated in times of encumbrances or endangerments, stress is said to have excitatory effects on the HR. Parasympathetic activity on the other hand, activated in times of relaxation, causes inhibitory effects on the HR (Delaney & Brodie, 2000; Taelman, Vandeput, Spaepen, & Van Huffel, 2009).

In the medical domain, mental stress, as in daily hassles, work related stress, psychosocial stress and stress among other domains is widely known for its negative long-term impact on the human health (DeLongis, Folkman, & Lazarus, 1988; Stawski, Cichy, Piazza, & Almeida, 2013). A study of Chiang, Turiano, Mroczek and Miller (2018), for instance, has found a positive association between the number of daily mental stressors, experienced within a naturalistic setting and the 20 year follow-up mortality risk of 1346 middle-aged adult participants.

Most detrimental and even fatal is the fact that mental stress is a high risk factor for cardiovascular diseases such as the coronary heart disease, myocardial infarction and cardiovascular death (Chandola et al., 2008; Das & O'Keefe, 2006; Hagström et al., 2018). Therefore, the underlying cardiac processes of mental stress have become of increasing interest in order to get to know more about their contribution to cardiovascular diseases.

As demonstrated in a study of Vrijkotte, Van Doornen and De Geus (2000), psychological stress is nowadays frequently associated with increased HR, and decreased heart rate variability (HRV) mediated by the autonomic nervous system (Delaney & Brodie, 2000; Sin, Sloan, McKinley, & Almeida, 2016; Taelman et al., 2009). A number of studies that made use of the Trier social stress test (TSST) demonstrated an increase in HR when being faced with a stressor. Here, however, stress was not assessed in a natural setting, but was instead artificially provoked in a laboratory. There participants are unexpectedly confronted with the task to prepare and conduct a presentation in front of an unknown jury, which is followed by a mental arithmetic tasks (counting backwards from 1022 in steps of 13) (Kirschbaum, Pirke, & Hellhammer, 1993; Rimmele et al., 2007). Although such studies did find significant correlations with HR, the laboratory setting cannot represent a person's daily life. Furthermore, mental stress is simply assumed, without taking an individual's stress perception into account.

Furthermore, the above mentioned findings refer to between-person correlations of HR/HRV and experienced stress, with only the mean data of individuals being compared. When analyzing the data on the so-called inter-individual level, researchers rely on averaged findings of a variable. Summarizing statistic methods like proportions, means and variances are then applied in order to analyze the obtained data. Findings of the individual are not differentiated and taken into account separately, but are aggregated together for the whole population. The purpose of finding general laws that are applicable for the individual can therefore often not be fulfilled, as there exist individual differences, or the correlation of two variables differs within-person when compared to only looking at averages. It is possible that a correlation which was found inter-individually does not exist on the individual level, namely the level on which the action takes place (Hamaker, 2012).

Taken together, inter-individual findings of the association between HR and mental stress may not be transferable to the individual. Nevertheless, these implementations for the individuals can increasingly be found in today's world. With the use of the above mentioned wearables people do not simply want to be informed about their physiological state (as their HR), but also utilize this data with the intention to monitor and manage their stress level

(Piwek et al., 2016). They thereby practically implement an intra-individual correlation without sufficient empirical support for its existence. So, despite of the simple handling and promising expectations of health benefits that come along with wearables, there is also a high potential risk of misuse. Given information, such as the HR, may lead users to draw wrong conclusions about their mental state. Furthermore, the devices which directly interpret the user's HR data, such as affective wearables, may not give reliable information about mental states. Thus, the user might get misled. In addition to that, possible moderating variables on the correlation with HR, such as chronic stress, are not considered by such wearables or their user (Piwek et al., 2016).

For the current research it is thus advisable to additionally examine the intra-individual, or within-person correlation of HR and experienced daily stress. This provides a more in-depth look into the processes and the individual interaction of the two variables, and allows to control for possible individual differences (Hamaker, 2012).

Furthermore, it is indicated by several studies, such as by Cohen et al. (1998), that the correlation between cardiovascular parameters and experienced stress does not only differ between inter- and intra-individual analysis, but also that continuation of stress experience moderates this correlation. In that study, changes of HRV as a response to stressful stimuli were examined among 9 PTSD (post traumatic stress disorder) patients as well as among a matched control group of 9 healthy volunteers. The results showed an effect of the stressful stimuli on HRV in healthy participants, whereas the PTSD participants showed almost no autonomic response. Similar findings were obtained in a study of Cohen et al. (2000). Here, in addition to lowered HRV, HR was also found to be heightened in PTSD participants and panic disorder patients at rest. As a possible explanation, Cohen et al. (1998; 2000) supposed that participants with chronic stress already experience such a high degree of cardiovascular response at rest that they are unable to show a further increase in their response when faced with a stressful stimuli. This is supported by the fact that the PTSD participants' cardiovascular reactivity at rest was similar to the reactivity of healthy participants when faced with a stressor.

That and most other studies, however, address the cardiovascular parameter HRV (Delaney & Brodie, 2000; Nolan et al., 1998; Sin et al., 2016). HRV is the variation in the heart's beat-to-beat intervals, thus the variation in time that passes between two consecutive heart beats. It serves as an indicator of the human body's ability to adapt to external influences (Sin et al., 2016). While high HRV implies a high capacity for adaption and therefore a well-functioning heart, low HRV is a predictor for increased mortality after an acute myocardial infarction (Kleiger, Miller, Bigger, & Moss, 1987) and heart failure (Nolan et al., 1998). Furthermore, low HRV has been linked to the appearance of depression in patients with coronary heart disease (Stein et al., 2000). Despite the broad implementation of measuring HRV for scientific research about stress, this method has its limits. Either measured by an electrocardiogram (ECG) or photoplethysmography (PPG), a long period of continuous measurement is needed in order to get reliable data (Levitan & Lewkowicz, 2004; Sandercock, Bromley, & Brodie, 2005). Furthermore, the measurements are highly susceptible for movement such as tilt, and work best at rest. This implicates a high impairment for measurements in natural settings, as movement (of e.g. the wrist on which a wearable is worn) is inevitable (Levitan & Lewkowicz, 2004).

For this research it was therefore decided to use HR instead of HRV as the cardiovascular parameter to be associated with stress. This is a reasonable alternative, as HR, alike HRV, is triggered by the sympathetic nervous system (Taelman et al., 2009). In contrast to HRV, HR, measured by a PPG (see appendix A), provides reasonably accurate data, even when deployed during physical activity and movement (Stahl, An, Dinkel, Noble, & Lee, 2016).

In order to improve the process of generating information about stress from physiological parameters, the first research question of this study considers whether HR serves as a reliable indicator of experienced stress in daily life. Both, inter-, as well as intra-individual correlations between HR and experienced stress will be examined. With regard to the findings of Cohen et al. (1998) it is additionally investigated whether this association between the two variables differs between high- and low-stressed people. It thereby can be analyzed whether constant stress serves as a moderator for the link between experienced stress and cardiac parameters.

Method

Participants

As this is a follow-up study, 18 participants have already been obtained half a year earlier in a study of Krüger (2018). The data of these 18 participants was added to the data of the current study. For this study, 20 new voluntary participants have been recruited through convenience sampling. This totalizes 38 participants, whose age varied from 19 to 45 years of age (M = 22,0, SD = 4,47). The participants were either Dutch, English or German native speakers. The research was approved by the ethics committee of the faculty of behavioral sciences of the University of Twente and a printed informed consent was subscribed by each participant.

Materials

Prior to the measurements an informed consent was used, by which the participants were informed about their rights, the usage of their data and the premises of the research.

In order to obtain the participants' HR, the wearable research device Empatica E4 was employed. Through photoplethysmography (PPG), the wearer's blood volume pulse (BVP) is continually measured with a sample rate of 64 Hz and gets converted into its HR (see appendix A). Besides, the Empatica E4 obtains data of the physiological parameters skin conductance and temperature, as well as the acceleration of the device when worn on the wrist. However, this data was not used for the current thesis. With the device, the participants were given a clip-on adapter with a micro-USB slot and a micro-USB to USB cable allowing them to charge the device and transfer the data obtained over the day. Therefore, the participants were required to own a notebook or computer with a USB slot, on which the computer program Empatica Manager had to be installed. This enabled both the transfer of physiological data from the Empatica E4 device onto the computer, and its upload onto the website empatica.com/connect, from where the data could be downloaded by the researchers. The process of downloading and uploading the data occurred automatically when the device got connected to a computer on which the program Empatica Manager was activated.

In order to obtain data of the experienced stress level, the participants were asked to install the application mQuest survey on their smartphones. Thereby, a short questionnaire of six questions was prompted with a push notification every two hours for one week of measurement, two of which asked for each, the experienced stress-, and arousal level, as well as the valence of these experiences. One of the questions asked for each, the experience of the last minute, and the other retrospectively about the experience for the last two hours. The answer possibilities ranged from 0 (very low/very unpleasant) to 10 (very high/very pleasant). Only the data about the experienced stress level of the past two hours was taken into account for the study ('How much stress did you experience during the last two hours?'; see appendix B, figure B1).

Prior to, as well as after the measurements, the Toronto Alexithymia Scale (TAS-20) was undertaken by each participant. This questionnaire measures a person's ability to identify and reflect their emotions. The thereby obtained data was not used in the current study.

Lastly, a semi-structured exit interview was employed in order to find out about the participants' experiences during the measurements and their individual conception of stress. This information was not used for the analysis but for discussing the practical relevance of the obtained statistical results.

Procedure

After signing the informed consent, the participants were given oral instructions for their one-week-participation in the research. Hereafter, the TAS-20 was filled in with paper and pencil.

With help of the researchers, the participant was guided to install Empatica Manager on his own notebook and download the mQuest application on the smartphone. The researchers then logged on to the programs with accounts which were created for the participants. An Empatica E4 wearable with its equipment was then handed out with instructions on how to use it. The participant wore the device everyday for one week, activating it when putting it on the wrist in the morning after waking up. It was taken off in the evening before going to sleep. During this time, physiological data was obtained continuously without any additional action needed. The device then was connected with the computer every evening in order to charge and to download the obtained physiological data from it. Therefore, the computer program Empatica Manager had to be activated.

In addition, the participant received a push notification by the mQuest Survey application on the smartphone every two hours, with the invitation to fill in the short questionnaire of six questions. The time limit for this was 30 minutes after receiving the push notification.

After one week there was again a meeting with the researcher(s) to hand back the wearable device. Furthermore, the TAS-20 was undertaken a second time and a researcher held a final interview with the participant in order to ask for experiences and possible difficulties that the participant might have encountered during the measurements. Lastly, he/she was thanked for the participation, had the chance to ask questions and received the researcher's e-mail address in case that any further questions should arise.

Analysis

Collected data from the E4 was integrated with the data from the questionnaires. Data was preprocessed with Matlab to synchronize the self-reported stress values with the average

HR values for every two hour period experience sampling signal. Subsequently, data analysis was done with SPSS (see appendix C). In order to handle missing data, each time specific set of data (containing HR and specific experienced stress level for two hours) with at least one missing element was deleted.

Descriptive statistics (ranges, means, standard deviations) were calculated for the two variables HR and perceived stress.

The first research question considered whether the HR serves as a reliable indicator of an individual's experienced stress level. To test this within-person, the intra-individual correlations of HR and experienced stress of the last two hours were determined by calculating the correlation for each participant.

In order to investigate the second research question, whether HR as an indicator differs in reliability between high and low stressed people, the single intra-individual correlations were compared between the two groups.

To determine the inter-individual differences between a high-, and a low-stressed group, the sample was clustered into two groups, regarding the participant's mean stress level. Thereby, the participants were distributed in a way that the two groups have the biggest possible difference, without regard to the sample size of each group. High-stressed participants were coded with 2, low-stressed participants with 1. Splitting the sample into two groups allowed to differentiate two intensity levels of stress, while keeping the statistical power as high as possible.

It was tested for inter-individual differences between the two groups with the Mann-Whitney U-test. Additionally, the correlation between HR and reported stress for the past two hours was separately determined for each group and a two sample hypothesis testing for the correlations was applied.

In order to estimate the probability to find an existing middle-sized effect for mental stress on HR and therefore also to estimate the generalizability of the inter-individual findings the power was calculated, for the whole sample as well as for the two groups. This was done via the post hoc power analysis for Pearson's correlations. Here, the reverence values of Cohen, modified by Ellis (2010) for a moderate effect (0.3) were used.

Results

Participants Excluded

Due to excessive missing data, the participants 35, 37 and 39 have been excluded from the data analysis.

Descriptive Statistics

Group dispensation. In order to distinguish different intensity levels of mental stress, the participants were allocated to two groups, according to their mean stress level. With the clustering method, 18 participants have been ascribed to the low-stress group (M_{age} = 20.8, SD_{age} = 1.85) while the remaining 17 participants were assigned to the high-stress group (M_{age} = 23.2, SD_{age} = 5.97). All 18 participants of the low-stress descend from the study of Krüger (2018), while the 17 new participants of this study were allocated to the high-stress group (see figure 1).

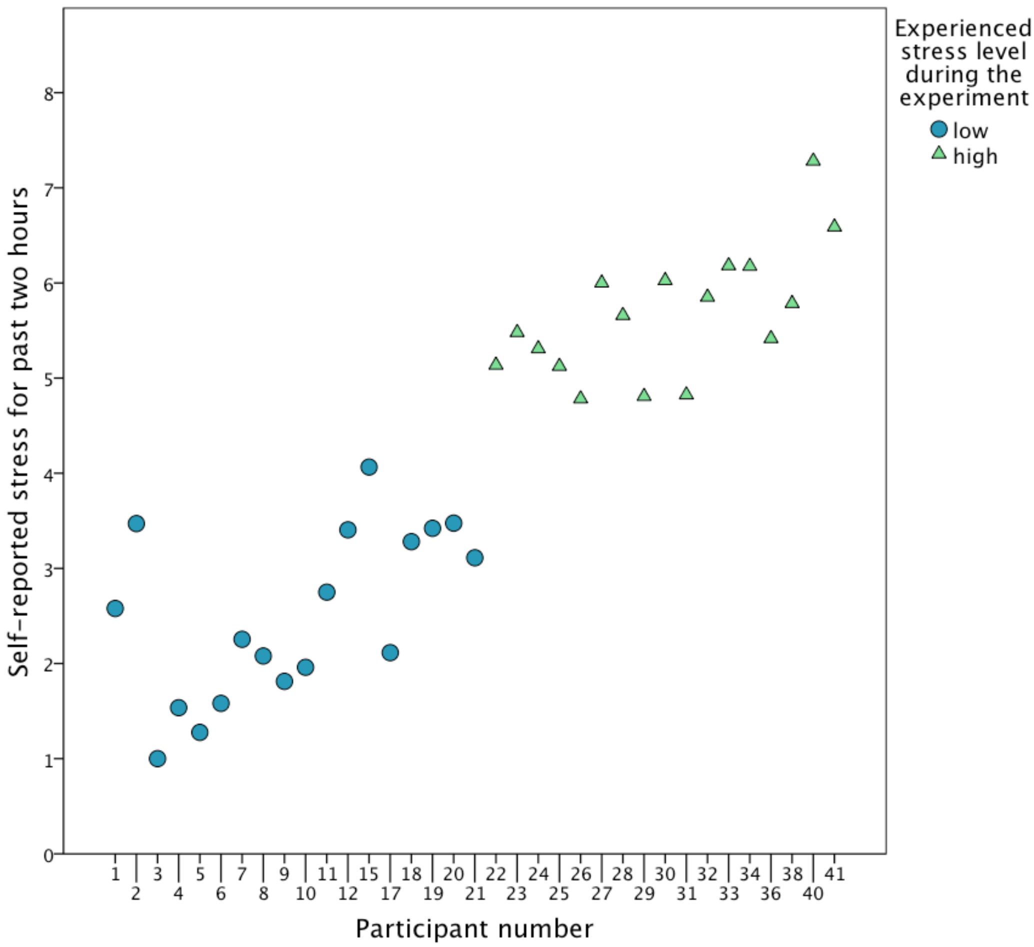

Figure 1. Mean self-reported stress per participant, sorted by stress level.

Heart rate. The physiological variable HR was continuously measured by the wearable device Empatica E4, that calculated HR from inter-beat intervals, and was averaged for intervals of two hours. The averaged experienced HR ranged from 65.5 to 93.6 (*M* = 78.9, *SD* = 6.33; see Figure 2). Participants of the low-stressed group had a mean of HR of 79.3, whereas the mean of the higher-stressed group was 78.4. The Mann-Whitney U-test was employed to test whether the two groups with different stress levels differ regarding their HR data. It showed no significant difference in HR between the groups (*p* = .73). This implies that the mean HR of the two groups are similar.

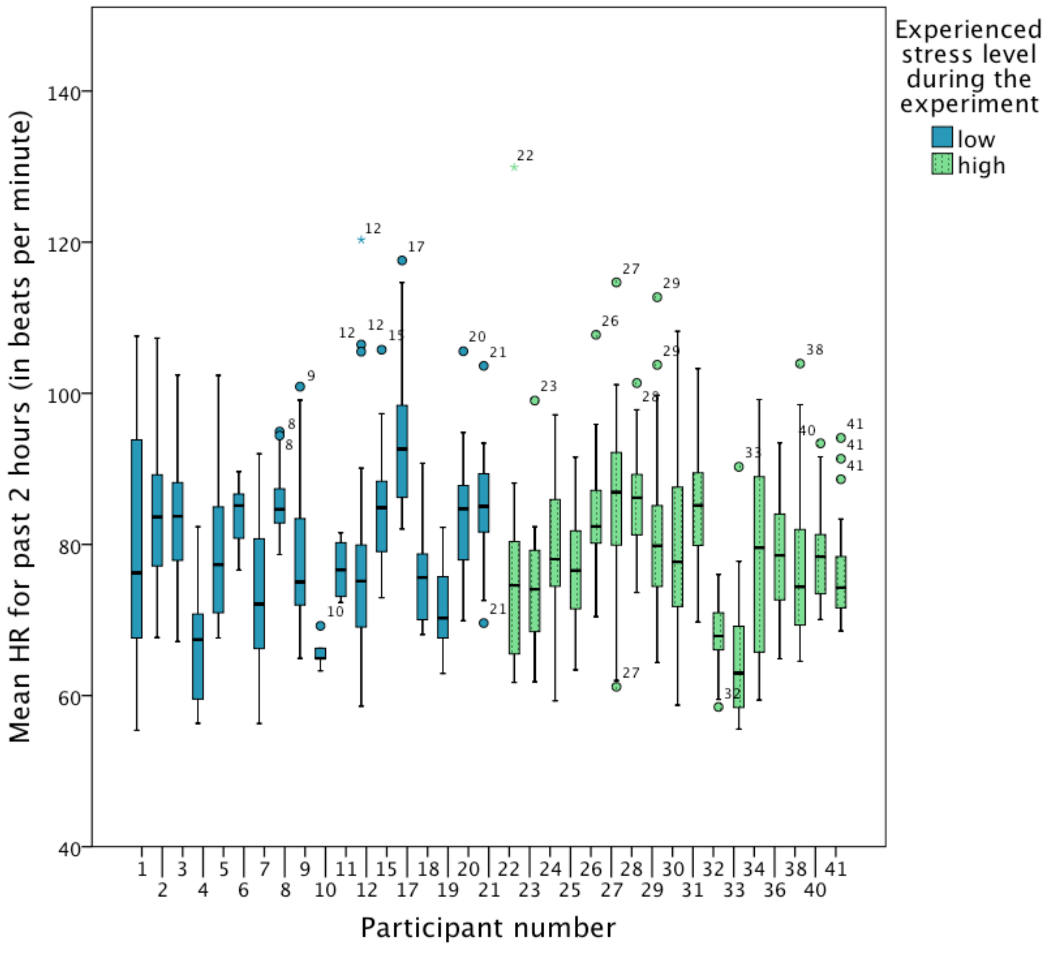

Figure 2. Mean HR for the past two hours per participant, sorted by stress level.

Perceived stress. The variable perceived stress was obtained through self-report, in which the participants were asked to assess their experienced stress level of the past two hours. The available scores ranged from 0 (=very low experienced stress) to 10 (=very high experienced stress). The averaged experienced stress of participants ranged from 1 to 7.28 (*M* = 4.13, *SD* = 1.76). Participants of the low-stress group had a mean of experienced stress of

2.59, whereas the mean of the high-stress group was 5.69, which differentiates the groups clearly (see Figures 1 & 3).

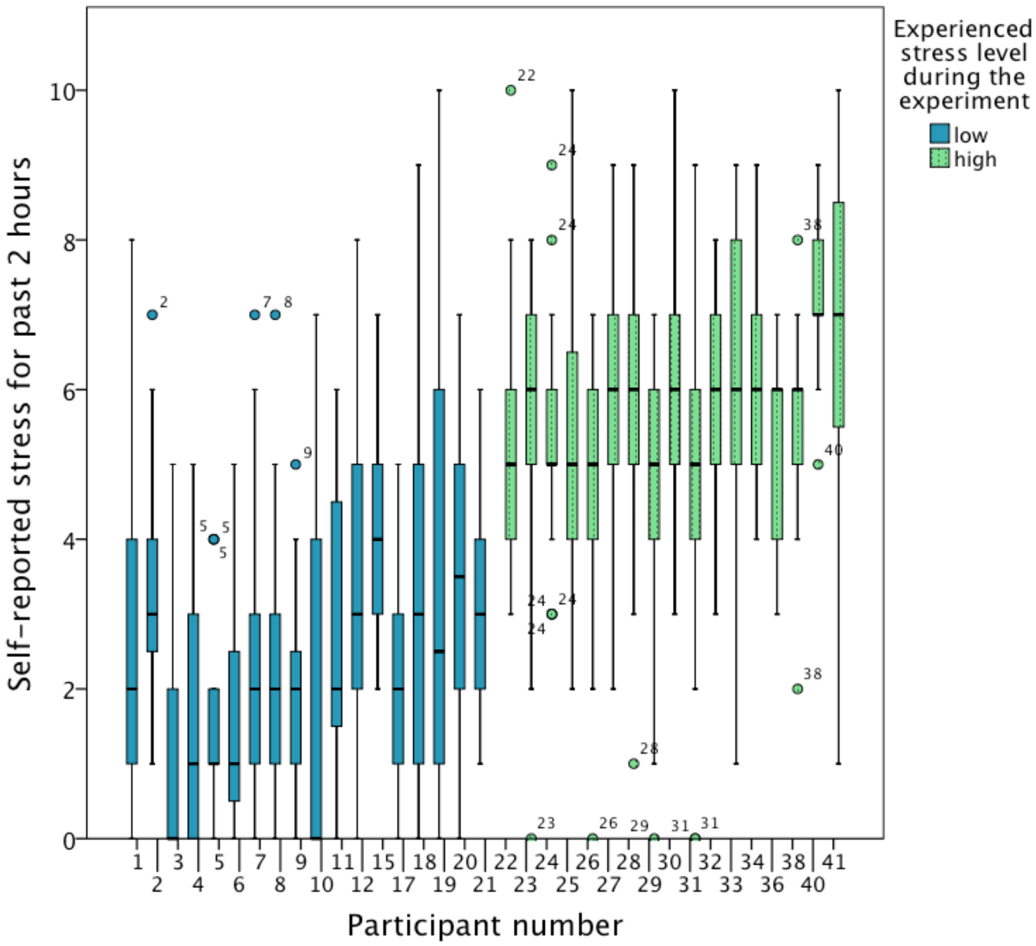

Figure 3. Self-reported stress for the past two hours per participant, sorted by stress level.

Correlating Heart Rate and Perceived Stress

Intra-individual correlations. In order to investigate whether HR serves as a reliable indicator of perceived stress on an individual level, intra-individual correlations were calculated for each of the 35 participants. Only three of them showed a significant intra-individual correlation between HR and the experienced stress of the past two hours. Participant 1 (Pearson's $r(26) = -.42$, $p < 0.05$) and participant 15 (Pearson's $r(31) = .47$, $p < 0.01$) are part of the low-stress group and participant 23 (Pearson's $r(42) = -.42$, $p < 0.01$) of the high-stress group. The total range of the intra-individual correlations went from $r = -.419$ to $r = 0.474$ (see Figure 4).

Intra-individual correlations groupwise. Within each of the two groups, negative as well as positive intra-individual correlations were found. No specific pattern of intra-individual correlations within the groups was found (e.g. mainly positive or mainly negative correlations). Therefore, the intra-individual correlations did not clearly differ between the two groups.

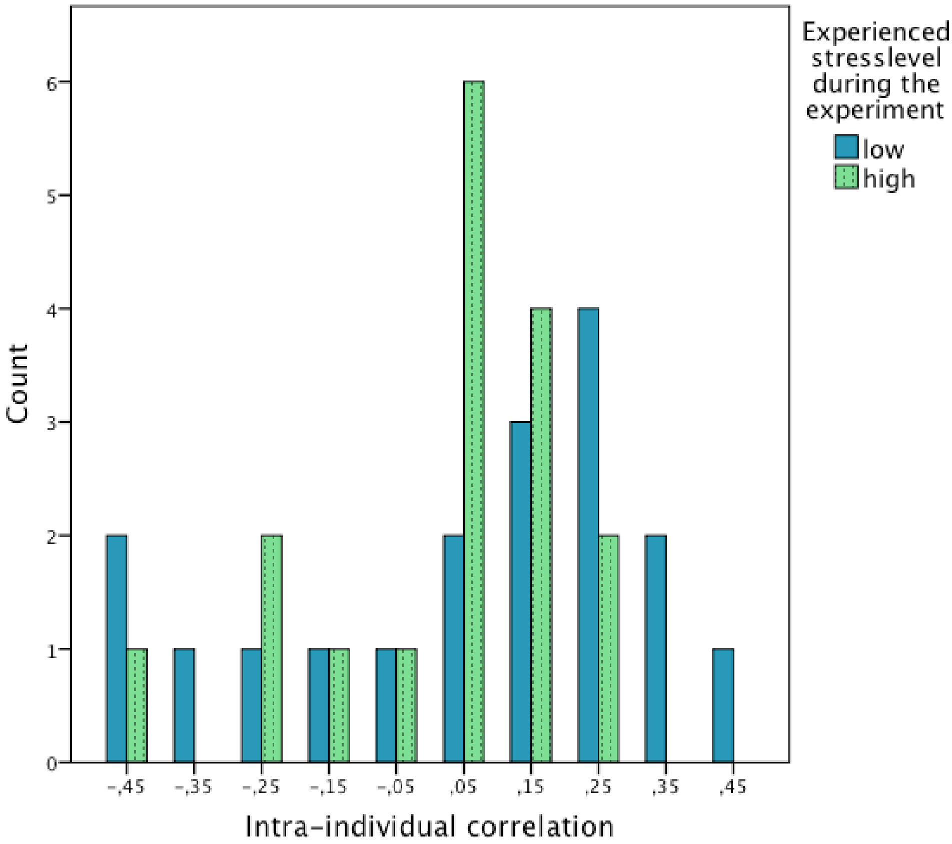

Figure 4. Clustered intra-individual correlation between HR and experienced stress for the past two hours, sorted by stress level.

Inter-individual correlations. In order to investigate whether HR and perceived stress are associated at a more general, between-person level, the inter-individual correlations of HR and perceived stress were calculated. There was found no significant between-person correlation between HR and perceived stress for the whole sample (Pearson's $r(35)= -.091$, $p = .60$). This correlation is inconsiderably small.

Inter-individual correlations groupwise. In order to investigate whether the intensity of the association between HR and perceived stress differs between high- and low-stressed people on a between-person level, first, the inter-individual correlations were calculated for the two groups. There was found no significant correlation between the two variables in the high- (Pearson's $r(17) = -.30$, $p = .24$) and the low-stress group (Pearson's $r(18) = .092$, $p = .72$). The correlation of the high-stress group is nevertheless moderately negative, whereas in the low-stress group it is positive, but inconsiderably small. Second, it was investigated whether these two correlations are significantly different from one another. The two sample hypothesis testing for correlation showed no significant difference in the correlation of HR and reported stress of the past two hours between the two groups of low- and higher stressed participants ($z < z_{crit}$) (see Figure 5).

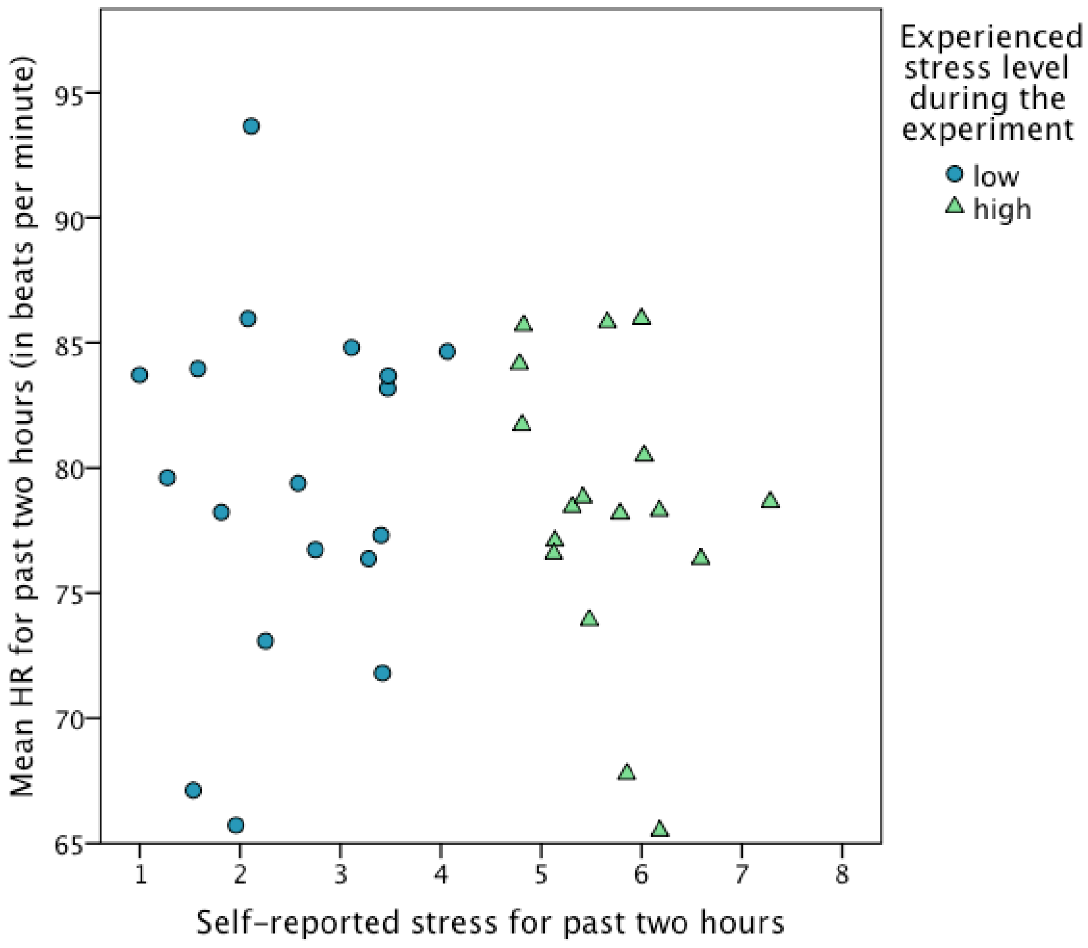

Figure 5. The correlation of self-reported stress for the past two hours and mean HR for the past two hours for the two groups of high- and low-stressed participants.

Power

The power was calculated in order to estimate the probability to find an existing middle-sized effect for mental stress on HR and therefore the generalizability of the inter-individual findings. For the whole sample of 35 participants, the power for the correlation of HR and perceived stress was calculated to be 0.44. This implies a insufficiently small power. By splitting the sample into two groups of 17 and 18 participants, the power for the low-stress group's correlation amounts to 0.24, whereas the power of the high-stress group's findings is 0.23. Therefore, the power of the two separate groups is also insufficiently small.

Discussion

The aim of this study was to investigate whether HR serves as a reliable indicator of experienced daily stress. It examined the within- and between-person correlation between HR and experienced stress obtained in intervals of two hours, while additionally discriminating between a high- and a low-stress group of participants.

Given the small proportion of significant intra-individual correlations, the results of these three participants are to be disregarded. On the basis of these intra-individual findings, with regard to the first research question, it is to assume that HR does not serve as a reliable indicator of experienced stress. This is supported by the fact that no significant correlation was found between HR and experienced stress inter-individually. However, the relatively small sample size of 35 participants causes an insufficiently low power for this inter-individual correlation. All conclusions that are drawn on the basis of these inter-individual results run the risk of not having found an actually existing and even significant correlation between HR and perceived stress. This deficiency might even explain the incongruity of inter-individual findings of this study and earlier studies, such as by Vrijkotte et al (2000) that did find a correlation between the two variables in question. Despite this restrictiveness of the inter-individual findings, with regard to the first research question it is to conclude that HR does not serve as a reliable indicator of experienced stress.

Taking a closer look at the second research question, regarding the influence of the intensity levels of stress, the findings are ambivalent. On the one hand, the intra-individual correlations of each group were positive as well as negative, and no pattern in the correlation's distribution became obvious that would differentiate the two groups. This indicates that the stress level does not serve as a mediator for the correlation between HR and perceived stress. On the other hand, inter-individually there was found a moderate (although not significant) negative correlation in the high-stress group and a small, but mentionable positive correlation in the low-stress group. This indicates that the intensity level of stress does moderate the correlation between HR and perceived stress even if this moderation is not strong. However, it is important to once more point out the restricted transferability of inter-individual findings onto the individual, as only mean data of a whole population is taken into account. Additionally, the power of the two separate groups is again insufficiently small. Therefore, the inter-individual findings are not sufficient for answering neither the first, nor the second research question. Instead, the intra-individual findings can be seen as more informative and applicable for answering these questions. Therefore, with regard to the second research question, the level of stress is assumed not to mediate a person's correlation between HR and perceived stress.

Regarding the practical transferability of the data, it also has to be taken a closer look onto the measurements of mental stress. Within this experiment, the participants assessed their subjective stress level, whereby it was aimed to 'grasp' what people themselves view as stress. This stands in contrast to earlier studies, such as by Vrijkotte et al. (2000) that operationalized stress with a model of Siegrist (Siegrist & Peter, 1994) and measured it with the 47-item Effort-Reward Imbalance questionnaire (Siegrist & Peter, 1994). The advantage of subjective measurements, as opposed to such operationalizations, are their everyday practicality. As exposed in the exit interviews, the participants' assessment of their stress level did not occur consistently, but several different understandings of what to perceive as stress were deployed. When being asked what indices they used for assessing their stress level, the majority was not able to give a clear answer (''It's hard to describe'', ''[I] didn't put many thoughts in it'') or mentioned different strategies (''The tension in the body, the brain, beats per minute of the heart and how my thoughts are organized'', ''I thought about what I did [...] if I had time stress or was rushing, [...] if I knew I still need to do things'', ''I am really stressed if [*sic*] I always think about a lot of things''). This indicates that the conception of stress differs among people, in the way that everyone is stressed by different events. Things that one person perceives as stress, might not be stressful for another. Supporting this, Cohen, Kamarck and Mermelstein (1983) explain that subjectively assessed stress is a final product of objective stressful events, coping capacities, aspects of the personality and more. This practicability is further supported by this study's natural measurement setting, which was achieved through the long measurement period of seven days and which took place in the participants' everyday lives. Therefore, it can be argued that the subjective self-assessment of stress which was applied in this study offers the opportunity to capture stress as it is perceived individually in daily life, instead of stress as a rigid concept that most people cannot relate with.

This practical relevance gives us the possibility to draw inferences about the use of ‘wearables’ on the basis of our findings. Given the missing connection of HR and perceived stress, one may conclude that data of HR, displayed by a wearable device such as a smart watch, does not give sufficient information to infer an individual’s stress level. This holds for low-, as well as high-stressed people, as there was found no difference between the two groups regarding their HR. Furthermore, affective wearables that interpret stress on the basis of someone’s HR presumably operate incorrect and therefore offer wrong information about their user’s mental state. People might try to avoid situations of alleged stress (e.g. someone avoids stairs because the bodily activity will increase the HR), which could lead to serious impairments of the daily life. As a consequence, it is advised against using such devices, especially when the aim of using it is to reduce, or gain control over one’s stress levels.

This also implicates that affective wearables based on HR measurements are not an appropriate tool to prevent cardiac diseases through stress monitoring. As the high- and the low-stress group showed no significant difference in HR it stands to reason that the high risk factor of cardiovascular diseases that comes along with mental stress (Chandola et al., 2008; Das & O’Keefe, 2006; Hagström et al., 2018), is not mediated by heightened HR. In fact, cardiovascular diseases are promoted by things such as hormonal homeostasis, as well as by self-destructive behaviors (e.g. noncompliance with medication, substance abuse, a poor diet), both activated by mental stress (Das & O’Keefe, 2006).

Besides this, there was a conspicuousness concerning the allocation of participants which is worth mentioning. As this is a follow-up study and the data gathering took place in two studies, one of them conducted half a year earlier (Krüger, 2018), there was an old and a new set of participants examined in this study. Interestingly, all 18 participants of the earlier study (numbered 1-21) have been allocated into the low-stress group. The 17 participants of the new study (numbered 22-41), on the other hand, displayed much higher levels of stress, by what they all got assigned to the high-stress group. Although very remarkable, a possible explanation for this distribution are two in this study newly added question regarding the valence of experience (’’How pleasant was your experience during the last minute/last two hours’’; see appendix B, figure B2). In contrast to the other questions regarding stress and arousal, the neutral point of reference was not 0 (=very low), but 5 (midway through 0=very unpleasant and 10=very pleasant). Thereby, the new participants might have transferred this scale onto the ratings of stress and arousal as well, making 5 the neutral point of reference. This assumption, however, is difficult and even impossible to prove on the basis of the existing data.

Regarding the findings and conclusions, however, potential limitations of this study have to be mentioned. The assignment of the participants into the low-, and the high-stress group occurred via a clustering method. Within this process the participants were not distributed according to their total stress level (criterion-referenced), but in proportion to the stress level of the whole sample (norm-referenced). It is therefore conceivable that participants of the high-stress group are not per se highly, let alone chronically stressed, but simply more stressed than the average stress level within the sample. An alternative would be to distribute the participants according to their scores of a questionnaire, which makes it possible to identify chronic stress. One example would be the Hassle Scale (Lazarus, 1990), an 117 item scale that emphasizes subjective daily hassles over major life events.

Furthermore, heightened HR caused by physical activity might have elevated the measurements of HR, and thus distorted the data, as the measurements were not adjusted for physical activity.

Yet another issue to discuss are the two hour time intervals between each report of perceived stress. It was earlier decided for this time interval, as the HR values were also averaged for two hours a time in order to even out inaccurate measurements. The participants were asked to evaluate their subjective stress level of the past two hours. As a study of Robinson and Clore (2002) pointed out, however, evaluating one's emotions (such as stress in this case) retrospectively comes along with a number of limitations. In contrast to reporting one's current emotions, retrospection requires the use of episodic memory in order to recall earlier emotions. Since emotion is probably not stored in memory directly, this recall is determined by beliefs about earlier emotions rather than the emotions themselves. In addition to that, more recent or more intense experiences can be retrieved easier and are therefore more likely to influence retrospective reports (Kahneman, 1999).

Taking a final view on this study, it can be said that the examination of intra-individual data provided a useful new insight into the actual association of HR and experienced stress within a person. The conclusions that were made based on the findings can be used to improve the practice of assessing stress through physiological parameters. As it stands to reason that the measurement of HR is not suitable for this assessment, with the help of this study the inappropriate usage of HR in this domain can be inhibited in the future.

Although this study offers this relevant implication, there is a lot more to be investigated when it comes to the assessment of stress. Not only HR, but also HRV is frequently used to 'measure' stress. Even though studies such as by Delaney and Brodie (2000) or Sin et al. (2016) demonstrated an association of HRV and stress, these studies again focused on inter-individual analysis and were conducted in laboratory settings. Given the earlier mentioned restrictions of this type of investigation that were pointed out by Hamaker (2012), especially when it comes to the implementation of such findings for an individual, further research about the intra-individual association of HRV and perceived stress will be needed in order to comprehend the actual association between these two parameters. Here again, it will further be important to keep the setting of measurements as natural as possible by integrating it into the participants' everyday lives.

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Appendix A

Photoplethysmography (PPG)

Photoplethysmography does not directly capture a person's HR, but derives HR data from measurements of the blood pressure. With each heartbeat the heart contracts, which leads to an increase of blood pressure in the heart's left ventricle. This pressure pumps the blood into the body's arteries, causing them to swell briefly. This is what can be felt as a pulse when feeling someone's wrist or neck. Photoplethysmography obtains this volumetric change through a LED light that is integrated into the Empatica E4 wristband and that shines directly onto the wrist. Each increase in blood pressure and swelling of the arteries will cause measurable differences in the reflection of this light. The strength of the hereby obtained signal is directly proportional to the pulse's pressure. Therefore, each peak of the signal signifies a heart beat. The variable HR stands for the amount of heartbeats per minute.

Appendix B

Screenshots of the mQuest questionnaire

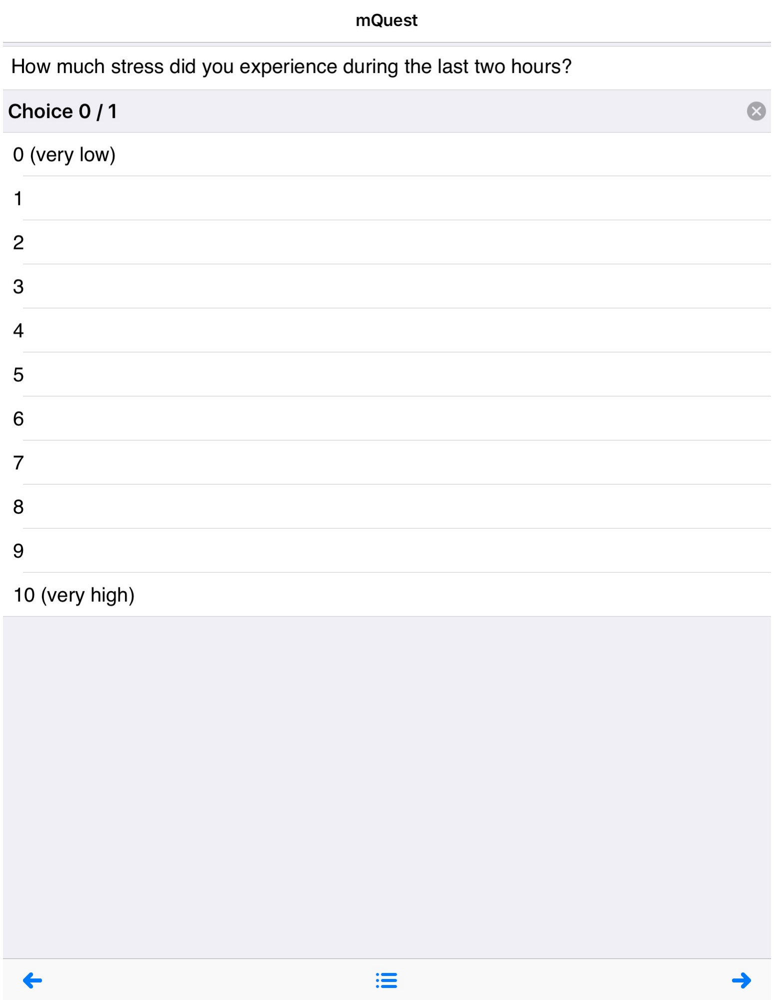

Figure B1. Screenshot of the question 'How much stress did you experience during the last two hours?' with rating from 0 (= very low) to 10 (= very high).

Figure B2. Screenshot of the question ’How pleasant was your experience during the last two hours?’ with rating from 0 (= very unpleasant) to 10 (= very pleasant).

Appendix C

Syntax

```
*Intra-individually: How are experienced stress and HR related -> Pearson correlation*

Sort cases by id.

Split file by id.

CORRELATIONS
  /VARIABLES=SR_stress_2hour HR_2hours
  /PRINT=TWOTAIL NOSIG
  /MISSING=PAIRWISE.

Split File off.


*Boxplot for visualizing the data*

EXAMINE VARIABLES=SR_stress_2hour BY id
  /PLOT=BOXPLOT
  /STATISTICS=NONE
  /NOTOTAL.

*First aggregation and clustering to get the high/low stressed information in this file*

AGGREGATE
  /OUTFILE=* MODE=ADDVARIABLES
  /BREAK=id
  /SR_stress_2hour_mean=MEAN(SR_stress_2hour)
  /HR_2hours_mean=MEAN(HR_2hours).

Variable labels SR_stress_2hour_mean "Mean experienced stress during the experiment".
```

```
Variable labels HR_2hours_mean "Mean HR during the experiment".

QUICK CLUSTER SR_stress_2hour_mean
  /MISSING=LISTWISE
  /CRITERIA=CLUSTER(2) MXITER(10) CONVERGE(0)
  /METHOD=KMEANS(NOUPDATE)
  /SAVE CLUSTER
  /PRINT INITIAL ANOVA CLUSTER DISTAN.

Variable labels QCL_1 "Experienced stresslevel during the experiment".
Value labels QCL_1 1 "low" 2 "high".
Execute.

* Chart Builder HR.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=id HR_2hours QCL_1
MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: id=col(source(s), name("id"), unit.category())
  DATA: HR_2hours=col(source(s), name("HR_2hours"))
  DATA: QCL_1=col(source(s), name("QCL_1"), unit.category())
  DATA: id=col(source(s), name("$CASENUM"), unit.category())
  COORD: rect(dim(1,2), cluster(3,0))
  GUIDE: axis(dim(3), label("Participant number"))
  GUIDE: axis(dim(2), label("mean heart rate past 2 hours"))
  GUIDE: legend(aesthetic(aesthetic.color), label("Clusternummer des Falls"))
  SCALE: linear(dim(2), include(0))
  ELEMENT: schema(position(bin.quantile.letter(QCL_1*HR_2hours*id)), color(QCL_1),
label(id))
END GPL.

* Chart Builder self reported stress.
```

```
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=id SR_stress_2hour QCL_1
MISSING=LISTWISE
    REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: id=col(source(s), name("id"), unit.category())
  DATA: SR_stress_2hour=col(source(s), name("SR_stress_2hour"))
  DATA: QCL_1=col(source(s), name("QCL_1"), unit.category())
  DATA: id=col(source(s), name("$CASENUM"), unit.category())
  COORD: rect(dim(1,2), cluster(3,0))
  GUIDE: axis(dim(3), label("Participant number"))
  GUIDE: axis(dim(2), label("self reported stress for past 2 hours"))
  GUIDE: legend(aesthetic(aesthetic.color), label("Clusternummer des Falls"))
  SCALE: linear(dim(2), include(0))
  SCALE: cat(aesthetic(aesthetic.color), include("1", "2"))
  SCALE: cat(dim(1), include("1", "2"))
  ELEMENT: schema(position(bin.quantile.letter(QCL_1*SR_stress_2hour*id)),
color(QCL_1), label(id))
END GPL.


*Second aggregation. Output saved in a new file*

AGGREGATE
  /OUTFILE='/Users/emilyfrye/Desktop/aggregated.sav'
  /BREAK=id
  /SR_stress_2hour_mean=MEAN(SR_stress_2hour)
  /HR_2hours_mean=MEAN(HR_2hours).

GET
  FILE='/Users/emilyfrye/Desktop/aggregated.sav'
```

```
DATASET NAME DataSet2 WINDOW=FRONT.

Variable labels SR_stress_2hour_mean "Mean experienced stress during the experiment".

Variable labels HR_2hours_mean "Mean HR during the experiment".


*Descriptive statistics and clustering for defining a high and low stressed group*

DESCRIPTIVES VARIABLES=SR_stress_2hour_mean
  /STATISTICS=MEAN STDDEV MIN MAX.

QUICK CLUSTER SR_stress_2hour_mean
  /MISSING=LISTWISE
  /CRITERIA=CLUSTER(2) MXITER(10) CONVERGE(0)
  /METHOD=KMEANS(NOUPDATE)
  /SAVE CLUSTER
  /PRINT INITIAL ANOVA CLUSTER DISTAN.


Variable labels QCL_1 "Experienced stresslevel during the experiment".
Value labels QCL_1 1 "low" 2 "high".
Execute.


* Chart Builder for relationship between self reported stress and Mean HR for past two
hours*
.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=SR_stress_2hour_mean
HR_2hours_mean QCL_1
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE.
BEGIN GPL
```

```
  SOURCE: s=userSource(id("graphdataset"))
  DATA: SR_stress_2hour_mean=col(source(s), name("SR_stress_2hour_mean"))
  DATA: HR_2hours_mean=col(source(s), name("HR_2hours_mean"))
  DATA: QCL_1=col(source(s), name("QCL_1"), unit.category())
  GUIDE: axis(dim(1), label("SR_stress_2hour_mean"))
  GUIDE: axis(dim(2), label("HR_2hours_mean"))
  GUIDE: legend(aesthetic(aesthetic.color.exterior), label("Clusternummer des Falls"))
  ELEMENT: point(position(SR_stress_2hour_mean*HR_2hours_mean),
color.exterior(QCL_1))
END GPL.


*Boxplot: Self reported stress for past to hours for high/low stressed group*

EXAMINE VARIABLES=SR_stress_2hour_mean BY QCL_1
  /PLOT=BOXPLOT
  /STATISTICS=NONE
  /NOTOTAL.


*Creating a new variable for manually inserting the intraindividual correlation and
participant's age*

COMPUTE intra_cor=0.
EXECUTE.

Variable labels intra_cor "intraindividual correlation between HR and stress during the last
two hours".

COMPUTE age=0.
EXECUTE.

Variable labels age "participant's age".
```

******!!!!!!! Execute the syntax to this point and then insert the intraindividual correlation and participant's age manually. When it`s done, go on with the execution!!!!!****

Interividually: How are experienced stress and HR related -> Pearson correlation. Not yet differentited by high and low stressed group

```
Sort cases by QCL_1.

CORRELATIONS
  /VARIABLES=HR_2hours_mean SR_stress_2hour_mean
  /PRINT=TWOTAIL NOSIG
  /MISSING=PAIRWISE.



Split file by QCL_1.
```

Descriptive statistics for mean HR and intraindividual correlation

```
DESCRIPTIVES VARIABLES=HR_2hours_mean
  /STATISTICS=MEAN STDDEV RANGE MIN MAX.



FREQUENCIES VARIABLES=intra_cor
  /STATISTICS=MEAN
  /ORDER=ANALYSIS.
```

Interindividual correlation between mean HR and mean self-reported stress

```
CORRELATIONS
  /VARIABLES=HR_2hours_mean SR_stress_2hour_mean
  /PRINT=TWOTAIL NOSIG
  /MISSING=PAIRWISE.

Split file off.
```

*Does the HR differ between the group with high or low stress?
Nonparametric Tests: Independent Samples. Mann Whitney U-Test*

```
NPTESTS
  /INDEPENDENT TEST (HR_2hours_mean) GROUP (QCL_1)
  /MISSING SCOPE=ANALYSIS USERMISSING=EXCLUDE
  /CRITERIA ALPHA=0.05  CILEVEL=95.
```

Descriptive statistics for age and HR

```
BOOTSTRAP
  /SAMPLING METHOD=STRATIFIED(STRATA=QCL_1 )
  /VARIABLES INPUT=HR_2hours_mean
  /CRITERIA CILEVEL=95 CITYPE=PERCENTILE  NSAMPLES=1000
  /MISSING USERMISSING=EXCLUDE.
DESCRIPTIVES VARIABLES=HR_2hours_mean
  /STATISTICS=MEAN STDDEV RANGE MIN MAX.

BOOTSTRAP
  /SAMPLING METHOD=STRATIFIED(STRATA=QCL_1 )
  /VARIABLES INPUT=age
  /CRITERIA CILEVEL=95 CITYPE=PERCENTILE  NSAMPLES=1000
  /MISSING USERMISSING=EXCLUDE.
DESCRIPTIVES VARIABLES=age
  /STATISTICS=MEAN STDDEV RANGE MIN MAX.
```

* Chart Building for intraindividual correlation*

```
IF intra_cor>=-1 and intra_cor<=-0.9 cluster_intra_cor=-0.95.
IF intra_cor>=-0.9 and intra_cor<=-0.8 cluster_intra_cor=-0.85.
```

```
IF intra_cor>=-0.8 and intra_cor<=-0.7 cluster_intra_cor=-0.75.
IF intra_cor>=-0.7 and intra_cor<=-0.6 cluster_intra_cor=-0.65.
IF intra_cor>=-0.6 and intra_cor<=-0.5 cluster_intra_cor=-0.55.
IF intra_cor>=-0.5 and intra_cor<=-0.4 cluster_intra_cor=-0.45.
IF intra_cor>=-0.4 and intra_cor<=-0.3 cluster_intra_cor=-0.35.
IF intra_cor>=-0.3 and intra_cor<=-0.2 cluster_intra_cor=-0.25.
IF intra_cor>=-0.2 and intra_cor<=-0.1 cluster_intra_cor=-0.15.
IF intra_cor>=-0.1 and intra_cor<=0 cluster_intra_cor=-0.05.
IF intra_cor>=0 and intra_cor<=0.1 cluster_intra_cor=0.05.
IF intra_cor>=0.1 and intra_cor<=0.2 cluster_intra_cor=0.15.
IF intra_cor>=0.2 and intra_cor<=0.3 cluster_intra_cor=0.25.
IF intra_cor>=0.3 and intra_cor<=0.4 cluster_intra_cor=0.35.
IF intra_cor>=0.4 and intra_cor<=0.5 cluster_intra_cor=0.45.
IF intra_cor>=0.5 and intra_cor<=0.6 cluster_intra_cor=0.55.
IF intra_cor>=0.6 and intra_cor<=0.7 cluster_intra_cor=0.65.
IF intra_cor>=0.7 and intra_cor<=0.8 cluster_intra_cor=0.75.
IF intra_cor>=0.8 and intra_cor<=0.9 cluster_intra_cor=0.85.
IF intra_cor>=0.9 and intra_cor<=1 cluster_intra_cor=0.95.
EXECUTE.
```

```
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=cluster_intra_cor
COUNT()[name="COUNT"] QCL_1
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: cluster_intra_cor=col(source(s), name("cluster_intra_cor"), unit.category())
  DATA: COUNT=col(source(s), name("COUNT"))
  DATA: QCL_1=col(source(s), name("QCL_1"), unit.category())
  COORD: rect(dim(1,2), cluster(3,0))
  GUIDE: axis(dim(3), label("cluster_intra_cor"))
  GUIDE: axis(dim(2), label("Anzahl"))
```

```
  GUIDE: legend(aesthetic(aesthetic.color.interior), label("experienced stresslevel during the
",
    "experiment"))
  SCALE: linear(dim(2), include(0))
  SCALE: cat(aesthetic(aesthetic.color.interior), include("1", "2"))
  SCALE: cat(dim(1), include("1", "2"))
  ELEMENT: interval(position(QCL_1*COUNT*cluster_intra_cor), color.interior(QCL_1),
    shape.interior(shape.square))
END GPL.
```

* Chart Building for self-reported stress for each participant; split by stresslevel*

```
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=id SR_stress_2hour_mean
QCL_1 MISSING=LISTWISE
    REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: id=col(source(s), name("id"), unit.category())
  DATA: SR_stress_2hour_mean=col(source(s), name("SR_stress_2hour_mean"))
  DATA: QCL_1=col(source(s), name("QCL_1"), unit.category())
  GUIDE: axis(dim(1), label("Participant number"))
  GUIDE: axis(dim(2), label("SR_stress_2hour_mean"))
  GUIDE: legend(aesthetic(aesthetic.color.exterior), label("Clusternummer des Falls"))
  SCALE: linear(dim(2), include(0))
  ELEMENT: point(position(id*SR_stress_2hour_mean), color.exterior(QCL_1))
END GPL.
```