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Development and evaluation of a cardiac coherence index for sleep analysis

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Cardiac coherence measurement is an established technology in biofeedback systems for stress release. Studies have typically been conducted with participants during ordinary waking consciousness, yet cardiac coherence during sleep may be even more important in illness prevention and health promotion. We investigated whether it was possible to develop an alternative effective technology: the Cardiac Coherence Index (CCI), for sleep analysis. The CCI is based on heart inter-beat interval spectral entropy and autonomic nervous system resonance analysis. We tested the hypothesis that the CCI could be a way to assess sleep quality and eventually as a tool to assess consciousness states during sleep. Our analysis suggests that high CCI corresponds to deep sleep stage, low CCI to awake state, and medium CCI to dream state. These findings further suggest that the CCI method is potentially a useful tool for the study of consciousness and as a home-based system for sleep management.

Keywords: cardiac coherence, consciousness, quality of life, sleep continuity, sleep stages, stress

Introduction

> *"It was early morning when I woke finally from another bad night's sleep. My sleep has been getting worse for days and I feel so exhausted all day long that I cannot get through my usual daily activities"* – (anonymous)

This type of comment is becoming the norm in our busy modern life as an increasing number of articles appear in newspapers and magazines about the problem of poor sleep and its impact on our quality of life and health (International Labour Organisation, 2004; Medic, Wille, & Hemels, 2017; Talbot, McGlinchey, Kaplan, Dahl, & Harvey, 2010). In general, we can identify some causes of poor sleep. These include chronic stress, chronic illnesses, an unhealthy sedentary life style, over eating, jetlag from traveling, lack of healthy social relationships, and emotional over-stimulation (Kervezee, Kosmadopoulos, & Boivin, 2018; Talbot et al., 2010).

While several sleep quality questionnaires exist (Ibáñez, Silva, & Cauli, 2018); assessing sleep quality from physiological data is a difficult problem due to the lack of consensus on the best metrics to use (Mendonca, Mostafa, Morgado-Dias, Ravelo-Garcia, & Penzel, 2019; Rosipal, Lewandowski, & Dorffner, 2013). Indeed, objective sleep quality metrics never provide satisfactory correlations with subjective metrics (Jackowska, Dockray, Hendrickx, & Steptoe, 2011). Additionally, the "gold standard" of clinical sleep assessment, polysomnography (PSG), is costly and not adapted for home use (Rohling, Blankvoort, Mattern-Coren, & De Weerd, 2013), thus limiting its early screening capacity. This points to the need for (i) home-located or body-worn physiological instruments capable of capturing objective and subjective sleep metrics; and (ii) a much better understanding of sleep structure and consciousness dynamics. This study attempted to address these two issues by validating measures of cardiac and respiratory function.

First, we applied recent developments in measuring cardiac and respiratory function and their mutual coupling during sleep (Burch et al., 2019; Penzel et al., 2016b; Sola-Soler, Giraldo, Fiz, & Jane, 2015a). This was done to develop a new cardiac coherence index that shows relevant correlations with gold standard polysomnography-based hypnograms. The proposed Cardiac Coherence Index (CCI) takes into account cardiac coherence and autonomic nervous system (ANS) resonance. The CCI is easily computed from the heart inter-beat intervals (IBI), which can be extracted from either the electrocardiogram or photoplethysmogram. Second, we employed a new perspective on the sleep-continuity structure based on the IBI. The new perspective is a universal scaling law across waking and sleep states (Ivanov, 2006) in concomitance with nature's scaling law from the quantum level to life, human behaviour, and the cosmos (West & Brown, 2004). This has deep implications in terms of understanding the relationship between human physiology, psychology, and the wider environment. Thus, we aimed to explore the behaviour of inter-beat intervals during sleep and their relationship to sleep structure based on the multi-scale dynamics of heart, brain, and heart-brain connection (see also Drouot et al., 2014; Kokosińska, Gierałtowski, Żebrowski, Orłowska-Baranowska, & Baranowski, 2018; Lin et al., 2014; Miskovic, MacDonald, Rhodes, & Cote, 2019; Rosipal et al., 2013), by using the proposed CCI.

The social and individual importance of sleep

Sleep was often understood by ancient cultures as a place and time where the body and mind could rest and recover from daily activities (Yetish et al., 2015). Our era is just rediscovering, mostly using physiological data and psychological assessment developed after 1950, what our ancestors already understood: That sufficient sleep is essential for our physical, mental, and spiritual health (Medic et al., 2017).

Traditional sleep beliefs

There are a range of traditional beliefs and earlier western attitudes regarding the state of sleep. For example, for Indian and Himalayan cultures, deepest sleep resonates with all and ultimate reality (Wilber, 2016). This is to be referred to as "absolute reality" in contemporary western debates around this matter (Bruza & Ramm, 2019; Mukhopadhyay, 2019). Whether experienced as mundane or divine, it is a "place" vital for life, love, and light experiences. In other words, sleep is that place of perfection to which one returns every night (Wilber, 2016). From an African ancestral perspective, this place of perfection is found in deepest dream consciousness through communication with an ancestor or ancestral community (Edwards, 2011).

In addition to the deep sleep state where we know we are always and already perfect, there exist intermediate dream-states (Wilber, 2000). The San people place great emphasis on dreams (Katz, 1982). Australian Aboriginal people speak of the Dreaming where one "goes walkabout". American First Nations speak of a vision quest. Experientially, when one meditates in the twilight, great visions can be revealed as if from some non-local realm of greater truth and values (Wilber, 2016). Thus, in earlier times, people would speak of one's soul leaving the body at night and returning in the morning. Zulu healers conduct ancestral ceremonies to integrate the soul of the diseased person with the collective family/ancestral spiritual body. This is called *ukubuyisa* (Edwards, 2011).

European esoteric traditions include such categories as etheric and astral bodies to distinguish layers of the energy body (Wilber, 2000, 2007, 2016). Hindu traditions speak of chakras, while Taoists distinguish various forms of qi (Ni, 1995) – the constantly flowing energetic network pervading both lifeforms and the universe (Francis, 2005; Jones & Ryan, 2006). Dream yoga has been practiced in Hindu and Buddhist traditions alike and is known to be both a healing and spiritual practice (Chenagtsang & Nguyen, 2013; Wangyal & Dahlby, 2004). Well-known European psychologists to have studied dreams and the collective unconscious include the seminal work of Jung (2016) and Mindell, Sternback-Scott, and Goodman (1982).

Contemporary sleep beliefs

Sleep states are mirrors of daily states (Lack & Wright, 2007). This has tremendous implications for each individual and society as a whole. During our days, the mind is constantly active with sense perceptions, memories, deep insights, feelings, and emotions. Each experience accumulates in our mind at some level (i.e. depth of consciousness) and can reappear in future awareness due to triggers such as memories, external stimulation, or body sensation (Wilber, 2000). We thus accumulate our own inner experiences, as well as those of others around us, more strongly if we have bonds with these people. Thus, the closest family and friends are the most influential, followed by our local surroundings such as the village or workplace populace, then nation-wide, and planetary influences. During sleep, all these experiences are unfolded and processed by our mind, as in dreams (Wilber, 2007, 2016), and it seems that the greater the influence of the daily stimuli, the deeper they are grooved inside our psyche, to be unveiled at proper times, and during certain phases of sleep. Further, these sleep processes have a direct impact on our bodies whilst sleeping, and during the days following (Medic et al., 2017). Day after day, and night after night, we unconsciously absorb the feelings and bodily perceptions of many people around us, as well as environmental factors, which in turn influence our behaviour and life as a whole. We thus realise the mutual interaction of ourselves and all that surrounds us.

Different states of consciousness manifest throughout our life depending on our health, both physical and psychological, as well as during daytime or sleep (Blume, del Giudice, Wislowska, Lechinger, & Schabus, 2015) When circadian cycles are felt as a whole, we might feel a sense of coherence, balance, and harmony. Perfect sleep *coherence* may be experienced in what mystics refer to as constant consciousness, known in Hindu traditions as *turiya* or nondual realisation through *turiyatita* (Wilber, 2000). In the following section, we explore this concept of *coherence* in sleep in more detail.

Coherence in sleep

We often use the terms coherent speech, coherent thoughts, coherent behaviour, as meaning consistent with, appropriate to, or in harmony with the context (McCraty & Zayas, 2014). From natural science and engineering perspectives, systems and signals can be defined as being in a coherent state if they manifest a high degree of orderliness or low entropy (McCraty, 2017). During sleep, we experience different levels of consciousness while our body progresses towards a self-repairing mode. When this process is fluid, one's sleep passes through the different stages and is restorative (Wilber, 2000). In other words, we feel full of vitality when we wake up. These stages have been recently studied by sleep scientists and clinicians, especially since the development of instruments capable of measuring our physiology such as: electroencephalograms, electrocardiograms and electromyograms. Under the assumption that our physiology reflects our psychological states, these instruments have been very useful for the study of sleep (Carley & Farabi, 2016). The gold standard of sleep assessment is called polysomnography and may include all or part of the signals mentioned above (International Labour Organisation, 2004). The result of such an assessment is usually presented as a Sleep Profile containing what is called a hypnogram. This hypnogram is based on the assumption that sleep states can be classified into six discreet, successively deeper levels or stages, as follows: WAKE (Wakefulness), REM (rapid eye movements), and four stages of NREM (non-rapid eye movements): NR1, NR2 NR3, and NR4 (Blume, del Giudice, Wislowska, , Lechinger, & Schabus, 2015).

These sleep stages, which have been studied for some time, have been used to derive so-called sleep quality indices, which are supposed to measure how "well" a person has slept, or how good the restorative process was. Despite many efforts to develop such indices, the reality is that there is usually a poor correlation between them and the subjective feeling of restfulness or restoration. This points to the fact that we still do not fully understand the process and purpose of sleep, and even less how to measure it with instruments (Mendonca et al., 2019). As previously indicated, we sought to investigate a new measure of sleep quality based on heart coherence and the major role of the heart as a gatekeeper of our health.

The concept of heart coherence

Our main vital organ is the heart from which life springs. It is maintained for more than 80 years on average, with about 3 000 000 000 (3 billons) heartbeats. Additionally, it has been shown that the resting heart rate is a predictor of life span (Jensen, Suadicani, Hein, & Gyntelberg, 2013). Furthermore, the heart naturally beats in a very irregular way most of the time, which is referred to as "heart rate variability". This variability persists at different time scales – from seconds to years (Ivanov, 2006; Moser, Fruhwirth, & Kenner, 2008). Thus, in addition to the resting heart rate, this variability is important for maintaining a state of balance and optimal energy usage (Moser et al., 2008). Amongst recent discoveries is the fact that the heart rhythm manifests a state of *resonance* at a certain frequency which is around 0.1Hz, or a cycle of 10 seconds (Bernardi et al., 2001; Steffen, Austin, DeBarros, & Brown, 2017). Resonance occurs when heart rate variability is large and mostly exhibits a coherent state. This resonance is a manifestation of a deeper order in our body (Steffen, Austin, DeBarros, & Brown, 2017) and is thus linked but not the same to the concept of coherence cited above.

Heart rhythm and emotions

The state of coherence is measured by the heart rhythm, which in turn reflects and impacts emotions (Mather & Thayer, 2018; McCraty & Zayas, 2014). Emotions are specific feelings co-emergent with other psychophysiological phenomena, which have the greatest impact on our quality of life and on the whole of society (McCraty, Deyhle, & Childre, 2012). Emotions stand as the ground of many of our life habits. Intellect, emotions, and intuitions are intertwined. However, from an evolutionary perspective, emotions and intuitions came first (Wilber, 2000) and can thus be considered as early forms of "mind language". Thus, improving the self-regulation of emotions is the foundation for a healthier life, including better sleep; while good quality sleep is essential for increasing our capacity for emotional regulation (Gross & Muñoz, 1995; Palmer & Alfano, 2017; Watling, Pawlik, Scott, Booth, & Short, 2017). A medium to long-term lack of restorative sleep leads to mental and emotional dysfunction (Haack & Mullington, 2005), which is a growing societal and economic problem in the 21st century. The main reasons for poor sleep quality includes persistent mental stress, a lack of compassionate heart-response, and insufficient contact with nature in our busy daily lives (Medic, Wille, & Hemels,(2017). All these factors lead to a fragmented mind and lack of coherence in our life as a whole.

Coherence in HeartMath

Coherence is a core HeartMath concept. It implies logical argumentation, systemically related parts, harmony, interconnectedness, and consistency. This typically includes a global order where the whole is greater than the sum of the parts (McCraty, 2017). At the natural scientific level, auto-coherence or autocorrelation implies stability in a single waveform (the sine wave); while cross-coherence, phase locking, and resonance reflect harmony in various rhythmic activities (Strogatz, 2003). More specifically, when applied to the heart inter-beat intervals, coherence has been defined as the normalised band-limited spectral power that is centred around the main peak in the frequency band 0.04–0.26*Hz* (McCraty et al., 2009), where the autonomic nervous system resonates (Bernardi et al., 2001).

At the psychophysiological level, coherence may occur between positive emotions and cardiovascular, respiratory, and immune and nervous systems (McCraty & Zayas, 2014). At the human, interpersonal, team and social levels, coherence refers to dyads, couples, groups, organisations, and communities, where harmonious relationships promote efficient energy flow, communication, synchronisation, and collective action. At the global level, groups, nations, and countries working co-operatively could promote optimal ecological and planetary peace and harmony, which is one goal of the HeartMath Global Coherence Initiative (GCI), which was established in 2008 (McCraty et al., 2012).

Cardiac coherence in sleep

The discussion above leads to the question of how we can assess sleep quality from a more holistic point of view, while still keeping its measurement as simple as possible so that it can be undertaken at home without much equipment. The answer comes from using the concept of coherence as it pertains to many aspects of our life, including sleep. Each of the aforementioned sleep stages reflect different emotions as emerging from our memories, imprinted traumas and happy moments, as well as events of our recent past, both at an individual and collective level. Perhaps more importantly, from a psychological health perspective, coherence could indicate the quality of our life as a whole, and particularly function as an index of "mental stress". To achieve the goal of promoting health, we developed an extended coherence metric concept for sleep assessment which we now present below.

The CCI

The motivation for developing this cardiac coherence index were fourfold. Firstly, we wanted an index that would reflect aspects of both coherence and resonance. Secondly, we wanted to have an index that would reflect our concept of orderliness and low entropy in a more specific manner. Thirdly, we aimed for an index that would monitor the heart-brain-breathing connection without much sensor complexity. Lastly, we wanted an index that would be capable of revealing the subtle micro-structure of sleep. The relationship between heart, brain, and breathing rhythms has been well-studied using multiple sensors to extract each inter-beat interval of the breathing signal. These measures are called cardiorespiratory coupling, heart-breathing and heart-brain synchrony (Kabir et al., 2010; Niizeki & Saitoh, 2018; Penzel et al., 2016a; Sola-Soler, Giraldo, Fiz, & Jane, 2015b). These aspects are very interesting and complementary to the CCI, which is conceptually simpler and requires less equipment to measure.

Method

Sources of data

We used the Cyclic Alternating Pattern (CAP) study (Terzano et al., 2001) from the Physionet database (Goldberger et al., 2000) because it contains an electrocardiogram and hypnograms. We extracted the IBI from the electrocardiogram using a modified algorithm from Pan and Tompkins (1985). We used only normal subject protocols from the CAP study. These consisted of 16 healthy participants (mean age = 32 years, age range = 23 to 24 years; female = 9, males = 7). Sleep staging was performed by expert sleep clinicians using the Rechtschaffen and Kales rules (Moser et al., 2009) and the classes WAKE, REM, and NR1 to NR4 were assigned.

Measures and data analysis

Starting from an IBI signal as measured from a heart rhythm sensor such as an electrocardiogram or a photoplethysmograph, the CCI is computed from N successive indexed segments T_k;(k = 1, …, N) of 30 seconds IBI overlapping each other by 15 seconds[1]. As a first step, on each segment T_k, we computed the normalised power spectral density P_k in the frequency band 0.04Hz to 0.3Hz. Thereafter, we estimated the normalised spectral entropy H_k (Crepeau & Isaacson, 1990, 1991). This normalised spectral entropy would correspond to the previously described heart coherence as used by HeartMath (McCraty et al., 2009). For the second step, we localised the maximum peak of P_k at a frequency of f_k^c, and measured a normalised weighting distance $W(f_k^c, f^r)$ from the ANS resonance frequency[2]: $f^r = 0.1Hz$. The CCI for the segment k is then defined as:

$$CCI_k(f^r) = \sqrt{W(f_k^c, f^r)(1 - H_k)}.$$

The CCI is thus a geometrical average of the weighting function W and the spectral entropy H. The CCI is always between 0 and 1. The interpretation of the CCI is as follows: the CCI approaches 0 if the entropy H is close to 1 (low coherence) or if the weighting function W approaches 0, that is the main frequency peak f^c is far from the ANS resonance frequency f^r. The CCI is thus a measure of how the heart coherence is in resonance with the ANS.

The weighted distance satisfies the following conditions: $W(f^r, f^r) = 1$, $W(f, f^r) = 0$ if $f > 0.3Hz$ or $f < 0Hz$ and $W(f, f^r)$ is a monotonically decreasing function on each side of f^c. A typical family of weighting functions is described in the equation and shown in Figure 1:

$$W(f, f^r) = 1 - |(f - f^c)/(f^r - f^c)|^\alpha;\ \alpha > 0$$

As mental stress incidence in the population is becoming an urgent matter to address, it is useful to note that stress can be understood as a complementary aspect of coherence (Niizeki & Saitoh, 2012). Stress is thus seen as an incoherent rhythm or reduced interconnectedness capacity between the person and his/her environment (de Oliveira et al., 2014; Koch, Leinweber, Drengberg, Blaum, & Oster, 2017), and within the person. For example, a reduced brain-heart connectedness is often reflected during stress (Thome et al., 2017) and a lack of interpersonal communication capacity can also be measured as a de-synchronized state (Fuchs, 2001). For this reason, we introduce 1 – CCI as a stress level.

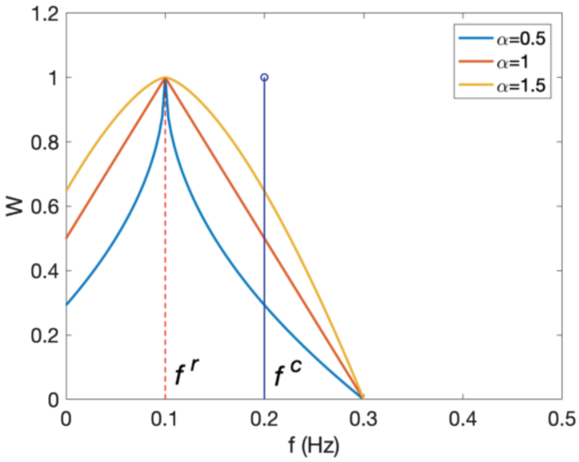

Figure 1. A family of weighting functions

Results

The CCI *and hypnogram*

We processed the IBI signals for the database and computed $CCI_k(f^r)$ according to the above formula for different values of the resonant frequency f^r; thus producing time (k) and frequency (f^r) heat maps. We fixed $\alpha = 1$. From this heat map, we computed the median CCI index at each instant k.

Stress level effects

Figure 2 shows two examples of the hypnogram and stress level analysis using 1 – CCI as the stress level. The colour coding for the stress heat map is as follows: the red zones indicate a high-stress level, while the blue zones reflect a more relaxed state of high coherence and slow breathing. The colour coding for the hypnogram is WAKE (red dots), REM (orange dots), and NR1 to NR4 from light to dark grey dots.

We can observe a correlation between the different sleep stages and the stress level: the higher stress is in the WAKE state, followed by the REM state, and progressively going down to the lower stress levels in the NR3 and NR4. We can also observe a striking correlation between the REM state and a sudden rise in the stress level. Once the REM state is in transition towards deeper sleep stages, the stress level drops almost continuously. The stress level tends to increase during the night until the person wakes up. The slow-wave sleep stage NR4 manifests the lowest stress level during the first part of the night for a long period, then again in NR4 at about 300 minutes after sleep onset, which is at about 50 minutes.

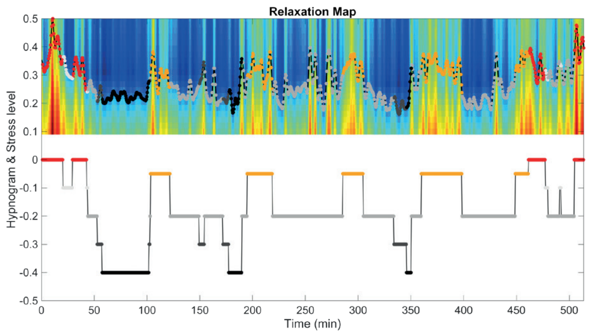

Figure 2. Stress heat map together with the hypnogram of a typical good night's sleep

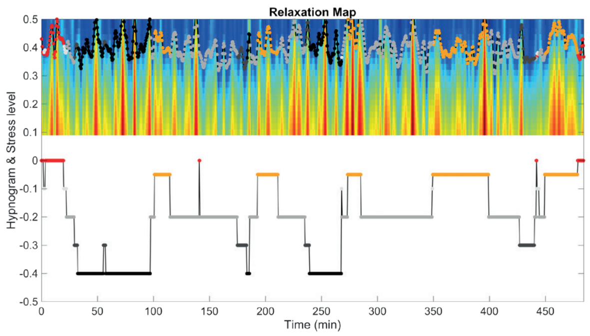

Figure 3. Stress heat map together with the hypnogram of a stressful night's sleep

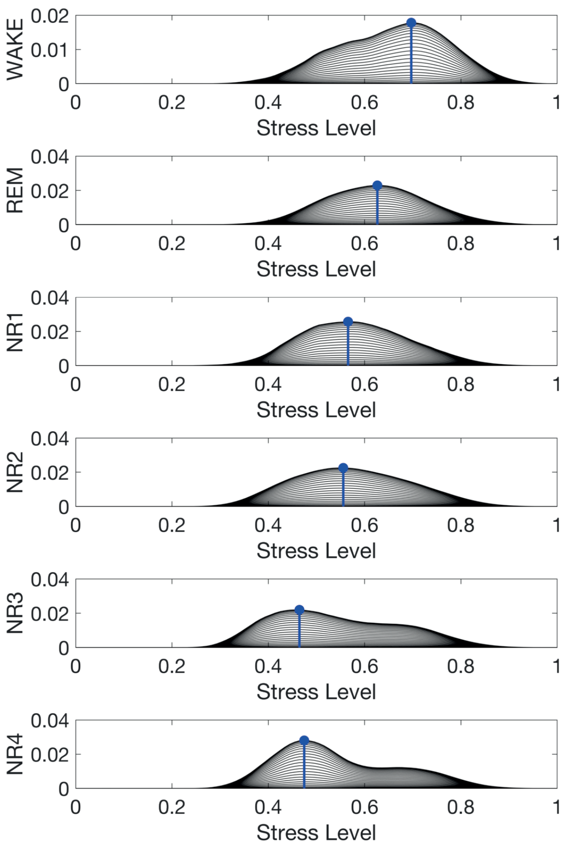

Figure 4. Stress level (1 – CCI) histograms according to the sleep stage

Macrostructure sleep staging profiling

Another type of sleep profile is shown in Figure 3. For this participant, the night's sleep was not good according to the participant's sustained high-stress level across the night, despite a reasonable hypnogram profile. This shows the difference between our CCI approach and the macrostructure sleep staging profiling. Specifically, the hypnogram does not even show a high level of fragmentation (Medic et al., 2017), which could be the results of the high density of the red zones in the stress heat map. Thus, in this case, there is another phenomenon occurring that is linked to a low level of heart coherence and/or fast breathing.

Lastly, Figure 4 depicts the normalised smoothed histograms (density functions) for each sleep stage of the stress level on the entire database. There is a clear trend of the stress level to decrease as the sleep depth increases from WAKE to NR4, from WAKE to NR2 and from WAKE to NR1. NR3 and NR4 show similar histograms (NR3 and NR4 have indeed been merged in the new AAMI standard of sleep staging) (Moser et al., 2009). NR3 and NR4 display a bimodal distribution with NR4 clearly pointing towards a low-level of stress. Our observations on this database show that the global shape of the CCI can be classified into four categories: (i) globally increasing, (ii) globally decreasing, (iii) globally constant (e.g. Figure 3), and (iv) with a 'banana shape' (e.g. Figure 2).

Sleep structure with CCI

The histograms presented in the previous section are quite gross level representations of the finer structure of sleep. Therefore, we analysed each sleep stage in more detail using a frequency sub-band decomposition known as *principal component analysis in state-space* (Schelter, Winterhalder, & Timmer, 2006). The purpose of this analysis is to discover different phenomena of sleep at different frequency scales.

Sleep frequency cycles

Figure 5 depicts a principal component analysis in state-space of 5 different frequency scales on one subject. The signal 1 – CCI is decomposed into different components $PC_i; (i = 1, \ldots ,5)$, which show up at different frequency bands and power. The signal 1 – CCI is shown at the top panel while the components are displayed on the left panels, with their corresponding frequency spectrum in cycles per minute on the right panels. The sleep stages are annotated on these signals with the same colour coding as in previous sections.

A first observation is the characteristic behaviour of the REM stage (orange dots), which always appears as a slowly decreasing wave in the first and second components PC_1 and PC_2. The slow-wave sleep stage NR4 appears on the increasing slope of PC_1 in the first part of the night, while stages NR1 to NR3 show up in increasing slopes later during the night. The REM stage seems to mostly appear as a slower CCI frequency as compared to the other stages. The PC_1 and PC_2 show a steady increase in amplitude towards the end of the night. It is interesting to note the frequency distribution from less than 0.01 *cycle/min* for PC_1 to about 0.1 *cycle/min* in the PC_5.

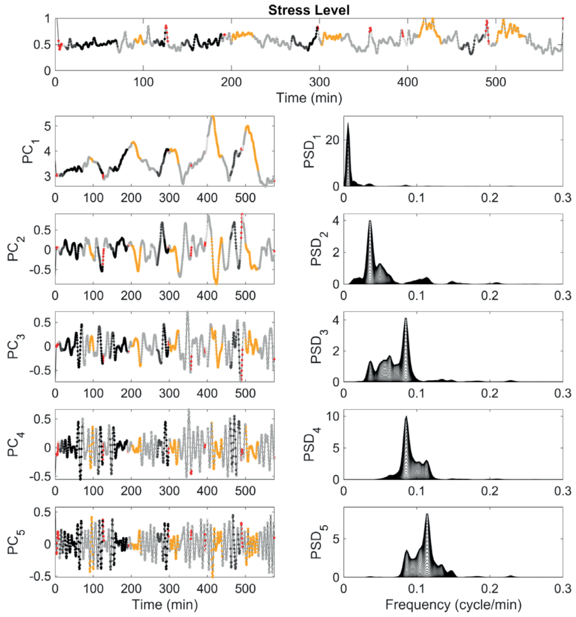

Figure 5. Multiscale analysis of the stress level according to the sleep stages for one subject

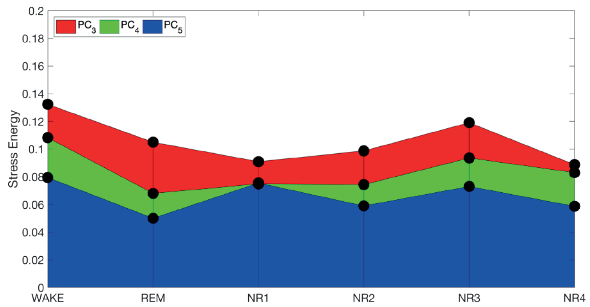

Figure 6. Multiscale analysis of the stress level according to the sleep stages on the entire database. Average values are shown

Lastly, Figure 6 depicts the power of each principle component for all participants and all sleep stages. We immediately notice the characteristic behaviour of REM with the lowest stress level power in the PC_4 and PC_5 (highest frequencies) and the largest power for WAKE in the PC_1 (lowest frequencies). NR3 and NR4 again show similar statistics across all frequencies, while NR1 and NR2 have distinct statistics for PC_5.

Discussion

Sleep is known to be a very important part of our life and the study of awareness and consciousness levels and their impact on our health and that of others is of great importance (Wilber, 2000, 2007, 2016). Using the CCI, the present study has shown that the heart-mind-breathing network is at work at different levels depending on the sleep stage. This finding clearly points to the close relationship between physiological and mental activities as cardiac coherence, cardio-respiratory coupling, and brain network synchrony has been proved to be linked with our mental state (Orme-Johnson, Clements, Haynes, & Badaoui, 1977; McCraty & Zayas, 2014; Niizeki & Saitoh, 2012; Thome et al., 2017; Faes, Nollo, Jurysta, & Marinazzo, 2014; Lutz, Greischar, Rawlings, Ricard, & Davidson, 2004; Gysels, Renevey, & Celka, 2005; Mather & Thayer, 2018).

This simple fact emphasises the relevance of the level of coordination of the heart rhythm: i.e. the different levels of order appearing in sleep (Chouchou & Desseilles, 2014). CCI analysis has confirmed the importance of the deep sleep stages NR3 and NR4, as it reaches its higher value there, meaning a high level of coherence close to the ANS resonance frequency. This phenomenon has also been observed during daytime naps (Cellini, Whitehurst, Mcdevitt, & Mednick, 2016). NR4 is the time of body and mind restoration as both of these aspects shows the lowest level of activity. It is during the NR4 stage that complete rest allows us to replenish our batteries, which are seemingly driven by a very subtle state of awareness. It is from this base awareness that other levels of consciousness emerge, engaging different mental processes and allowing the rise to total wakefulness at dawn as shown in hypnograms (Blume et al., 2015). A high level of CCI also means a low level of entropy of the heart rhythm in the frequency band 0.1 – 0.4*Hz*. Our finding that the CCI takes its lowest values during the NR4 makes it a potentially interesting quantifier of sleep quality, i. e., the longer the person stays in NR4, the greater the recovery capacity.

In terms of CCI, the REM state is close to the WAKE state; yet, each has different dynamics across the night. The REM state is known to be the time for dreaming and our analysis shows predominantly mid-frequency oscillations around 0.5 *cycle/min*. Additionally, the REM stage appears abruptly from deeper sleep stages showing low CCI. The REM stage is a very interesting consciousness state and quite different in nature from the other stages (Chow et al., 2013; Chouchou & Desseilles, 2014). Further, its study may lead to new discoveries in the understanding of consciousness and its relationship with physiology and our environment (Reddy & Pereira, 2017; Pylkkänen, 2019).

Implications for sleep studies and therapies

The usefulness of this new approach to sleep study, as well as the urgent need to assist people suffering from stress and other cardiac disorders (Kim & Dimsdale, 2007), has driven us to see the potential in using easy-to-wear physiological sensors to capture the heart inter-beat intervals. Undoubtedly, the most promising technology is based on optical sensing of the blood pressure wave (Kim & Dimsdale, 2007). The capture of cardiac and breathing patterns is accurate enough with wearable photoplethysmogram (PPG) sensors, while at rest or during mild movements (Jeyhani, Mahdiani, Peltokangas, & Vehkaoja, 2015) and especially for sleep assessment (Renevey et al., 2013; Carós, et al., 2014). Due to their small size, PPG sensors are the best candidates to implement our strategy.

Limitations of the study and suggestions for further research

The present study has some limitations. Firstly, the statistics extracted from this study have limited value due to the limited sample size. This will be improved in a future sleep study involving more participants. Secondly, we did not use a sleep quality questionnaire, thus limiting our conclusions regarding the analysis of sleep quality.

It seems likely that further research using the CCI will focus on meditative studies, states of consciousness and correlation with brain neuronal activity. For example, further study is indicated on relationships between the sleep CCI , brain synchronized networks, life style, sport, social activities and global group network practices such as those developed by the HeartMath Global Coherence Initiative (McCraty et al., 2012).

Conclusions

We investigated the use of cardiac coherence and autonomic nervous system resonance in the context of sleep. We developed a new index based on these two features and showed its relevance when compared to "gold standard" hypnograms. The new index showed positive correlations with different sleep stages and allowed us to interpret sleep from a new perspective of coherence across the different physiological and conscious states of the sleep. The simplicity of deployment of such sensing and processing will lead to inexpensive tools for assessing sleep quality, stress, relaxation, meditation, and yoga.

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Endnotes

1. The reason for choosing this duration of segment is that it coincides with gold standard polysomnography analysis.
2. The ANS resonant frequency is different in every person but always close to 0.1*Hz*. Ideally, we should measure for the individual resonant frequency of each person.

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