BREATHING PHYSIOLOGY AND GUIDED BREATHING EXERCISE: A PRIMER

by

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1 Introduction

Respiration, while primarily responsible for gas-exchange, is interconnected with the numerous other physiological processes throughout our bodies. Our breathing simultaneously both *influences* and *is influenced by* the state of our body more generally. Breathing is particularly interesting because, in addition to being an unconsciously-regulated (or *autonomic*) process, we have direct and volitional control over it. Therefore, when we choose to exert control over our breath we create change throughout the entire body. In fact, this type of active engagement with our breathing is involved in a variety of practices that support goals ranging from performance in sport to mindfulness in meditation [4]. Furthermore, standalone *guided breathing exercise* – active engagement with the breath practiced independently from other activities – has also been shown to have both immediate and long-term benefits for health, including reduction in the symptoms of chronic stress [22], lower blood pressure in individuals with hypertension [41], increased resistance to relapse in depression [8], increased effectiveness of substance dependence treatments [15], and increased cognitive executive functioning [37,46]. Given these documented health benefits (see [18] for a full review), it should come as no suprise that commercially available products exist to facilitate breathing exercises. For example, guided breathing tools such as HeartMath's *EmWave*[1] and MindMedia's *BioTrace+*[2] are marketed based on the promise of health benefits that can be achieved with continued use. Furthermore, guided breathing is a popular focus in HCI research both as a standalone exercise as well as the supporting role it plays in practices like meditaiton and mindfulness.

In this primer, we outline the basics of respiratory physiology and guided breathing exercises, clarifying the differences between commonly practiced breathing techniques, and explaining the expected acute physiological effects during the short-term application of paced breathing and HRV-b.

The goals of this primer are to:

- *Synthesize knowledge of breathing physiology* in a format that is accessible to HCI researchers who may not be experts in physiology or medicine, helping inform the design of technology-mediated guided breathing tools and digital design more generally
- *Provide a template* for design researchers exploring other areas of physiology to share their knowledge in similar ways, as we believe that there is valuable design knowledge to be discovered by exploring the countless other physiological processes in detail

2 What is Breathing?

Humans are aerobic. This means that, like other mammals, oxygen (O_2) is essential to many metabolic processes of the body. Metabolism in this sense refers to the processes of the body that convert an input into a different output [49]. For example, we metabolize whole food into various nutrients that in turn are metabolized (changed) into energy, new tissues, and so on.

Breathing, formally called respiration, brings O_2 into the body. More specifically, *external* respiration refers to the process of taking O_2 into the lungs, while *internal* respiration refers to how, once in the body, O_2 is pulled into the cells as part of these aerobic metabolic processes [7]. As O_2 is used by the body, water and another gas, carbon dioxide (CO_2), are produced [49], and respiration additionally serves as a mechanism for vacating excess amounts of these gasses from the body. The relationship between CO_2 and O_2 is particularly

[1] heartmath.com/emwave
[2] mindmedia.com/en/products/biotrace-software

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important, especially in terms of why we are focusing on breathing in this study. O_2 is carried to cells via the bloodstream and CO_2 is essential for moving the O_2 through the bloodstream and into those cells. When the ratio of CO_2 to O_2 changes from normal (from homeostasis), certain hormonal and associated nervous system responses are triggered that affect our overall state of being [39]. Therefore, how we breathe - the rate at which we exchange the O_2 and CO_2 gasses into and out of our bodies – is one of the key factors affecting this ratio and, consequently, our overall state.

3 Shallow Breathing and Deep Breathing

A full breath (i.e., drawing in oxygen to fill the alveoli in the lungs) involves a surprising number of muscles including those in the nose, throat, chest, back, and abdomen [7]. Culturally however, in the developed world, we tend to breathe with only a subset of these muscles – mainly those around our upper chest [7]. This chest-initiated breathing is often called "shallow breathing" and is largely a consequence of our predominately seated, sedentary lifestyle. While not intrinsically "bad", shallow/chest breathing physically limits the volume of gas that can enter the lungs, so when sustained for prolonged periods of time, chest breathing can create an imbalance in the body's O_2 to CO_2 levels, which can be detrimental to overall metabolism. Alternately, when breathing is instead initiated around the abdominal area such that the abdomen distends on inhalation and collapses on exhalation, greater volumes of air are permitted to enter the lungs. Breathing in this way is referred to as "deep breathing" [7] and makes use of, in particular, a muscle dedicated to a fuller inhalation: the diaphragm. While the mechanics of breathing are beyond the scope of this paper (see [7] for a detailed overview), the key difference between the two types of breathing (chest vs. abdominal) is the effect they can have on internal physio-neurological balance.

4 Shallow Breathing Can Lead to Imbalance in Autonomic State

When we initiate our breathing from the chest up, we can think of it as a partial breath: we get insufficient O_2 in that breath and, consequently, our respiration rate increases to make up for the lack of O_2 [49]. In a sense, our body is working harder to make up for the less efficient O_2 - CO_2 exchange that occurs during shallow breathing.

In addition to decreasing the efficiency of gas exchange in our lungs, changes in breathing also influence balance in our *autonomic nervous system*, otherwise known as *autonomic state*. Our autonomic nervous system (ANS) is responsible the regulating the non-volotional (or *autonomic*) processes that occur within our body such as digestion, temperature regulation, circulation, and (non-volitional) breathing. The ANS is composed of two opposing branches that are in dynamic balance with one another: the *sympathetic nervous system* (SNS) and the *parasympathetic nervous system* (PNS). This balance is important, becauase the functioning of the numerous autonomic processes within our body depends on which of these two branches is more dominant at a particular time. On the one hand, when the PNS is dominant (which typically occurs when we are relaxed and is often called the "rest and digest" response), our body favors restorative and regenerative processes such as digestion, cell regeneration, and reproduction. On the other hand, when the SNS becomes dominant (which typically ocurrs when we feel threatened and is often called the "fight or flight" response), these restorative proceses are put on hold in favor of more immeditate processes that could protect us from danger such as increasing our heart rate and blood pressure while simultaneously redirecting blood supplies to our limbs in preparation to protect our selves or make a quick get away.

It is important to note that the balance between the SNS and PNS (i.e., our autonomic state) is mediated by a host of possible causes. However, physiologically, shallow breathing does trigger and contribute to what is often framed as a stress (or threat) response. It is also important to clarify that *this shift to sympathetic dominance is not necessarily undesirable*. In fact, when we exercise, we also shift towards SNS dominance, where blood flow moves more from the core to the periphery to support our limbs in action [49]. One key difference between exercise induced SNS shifts vs. shallow breathing from sitting at a desk is *our response*. In exercise, we are responding physically to these hormonal signals to carry out a physical action. In physical exercise, the hormonal triggers causing the shift to SNS are addressed and flushed from the bloodstream, and the shift back towards PNS occurs as part of the body's recovery mechanism [49]. Furthermore, another key difference is that while physical exercise is typically an acute stressor – an event that happens for a short time and is finished – workplace stressors such as bullying, excessive workloads, fatigue, or even something as simple as persistent shallow breathing while seated at a desk can create a chronic or ongoing physiological state of stress [14]. This is particularly problematic because, unlike in physical exercise, there is no physical response to address the hormonal triggers causing the stress [23,33], which leads to the stress state being further amplified and/or prolonged causing a vicious cycle or feedback loop.

5 Stress isn't necessarily bad! Acute Stress and Chronic Stress

A key point is that stress is not "bad." Stress is the body's correct response to a perceived threat: it is to prepare us to protect ourselves. The problem, as with many issues in health, is when stress moves from being an acute incident to a chronic or ongoing one [9,21,27]. When stress becomes chronic, our bodies effectively stay in a state of sympathetic dominance, which means it is simply harder to sleep, to lose weight, to be creative, or even to be happy [49]: we are wired, as it were, to focus on threats. Beyond affecting our autonomic state and bodily balance, chronic stress can also have detrimental physical effects on our body. For example, a sustained increase in heart rate and blood pressure due to chronic stress means that not only is the heart working harder and contracting more often than it would otherwise, but the increased pressure in the circulatory system can create damage to the smooth inner walls of the vein and arteries, making the individual more susceptible to the effects of high cholesterol and heart disease over time [29].

6 Deep Breathing Can Help Restore Autonomic Balance

While shallow breathing is part of a set of behaviors that trigger a shift to the SNS, deep (and slower) breathing tends to reset the body to be more PNS dominant (i.e., by creating a shift back towards balance / homeostasis) [40]. One factor involved in deep breathing includes CO_2 and O_2 reaching balance, or homeostasis, as more lung capacity is being used in each breath. This also means that as this oxygenation of tissue (which does require CO2 to move the O2 through the blood stream) improves, it is easier for the body to carry out its various metabolic functions and therefore avoids a variety of other hormones that would otherwise be triggered to increase the heart rate to get more of the limited supply of oxygen to the tissue and, at the same time, increase breathing rate in an attempt to get more air into the lungs in the first place. Connections around the intercostal (rib related) muscles are stretched for inhalation, and the slower exhalation of CO_2 in breathing out also triggers a response that enables baroreceptors (nervous tissue in part responsible for managing blood pressure) to respond more sensitively (called *baroreflex sensitivity* [24,39], see below). All these states contribute to increased activity of the PNS, which in turn signals the limbic system of the brain (including the amygdala, hypothalamus, hippocampus, anterior cingulate cortex) to move away from a "threat" status towards a calmer, restorative state.

7 Breathing affects our Heart Rate – Heart Rate Variability

Even though breathing is the main mechanism of interest in this paper, there are numerous connections between our breath, heart, and autonomic state. In fact, the "effectiveness" of guided breathing exercises is often determined based on how they influence the patterns of our heart beat.

One of the simplest ways that the pattern of our heart beat can be quantified is through our *heart rate*, a measure of the number of physical contractions of the heart in one minute. However, heart rate itself is an average measure, as beat to beat times themselves vary. This variability is eponymously referred to as *Heart Rate Variability (HRV)* and is itself a strong measure of personal health and wellbeing [20,42,43,50] because greater variability arises due to increased sensitivity in the underlying physiological processes that drive this variation. Conceptually, HRV quantifies the variability in time intervals between consecutive heart beats. These time intervals are typically referred to as *RR-Intervals*, where "R" is the name given to the peak wave in the measure of electrical activity of the heart, measured in an electrocardiogram as it captures amplitude/time (in millivolts/seconds – see Figure 1) [42].

Measures of HRV can thus be computed in both the time-domain and frequency-domains. For example, the standard deviation of a series of RR-Intervals (SDNN), or the root mean squared variability of successive differences between RR-Intervals (RMSSD) are both commonly used time-domain measures of HRV. Alternatively, frequency-domain measures can be used to (roughly) decompose and identify the extent to which various physiological processes influence overall HRV. For example, the high frequency band of HRV (typically labelled as "HF") is identified as variability occurring between 0.15 – 0.4 Hz, as this is the range within which our resting breathing rate typically resides (corresponds to 9 – 24 breaths per minute). Similarly, the low frequency band (LF – 0.04-0.15 Hz) largely reflects the influence of the baroreflex (see next section) on HRV. Bands of even lower frequencies have also been used to capture variability from longer term processes within the body, such as temperature regulation, daily cycles, and circadian rhythm [42,43].

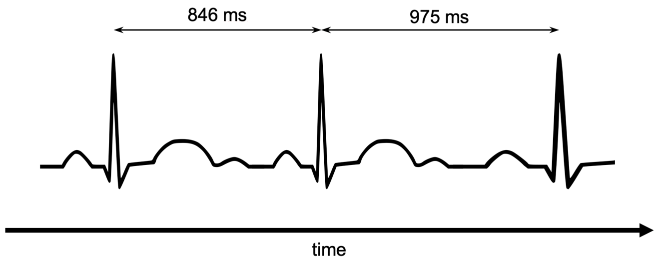

Figure 1: A hypothetical heartbeat signal demonstrating heart rate variability (HRV). The timing between each successive set of heart beats (known as an R-R interval) naturally varies in healthy organisms. Note that while the y-axis, while not labelled, represents the magnitude of heart contractions often measured in mV.

8 Physiological Sources of HRV affected during Guided Breathing Exercises: Respiratory Sinus Arrhythmia and the Baroreflex

Two physiological sources of HRV are of particular interest when practicing guided breathing exercises: *respiratory sinus arrhythmia (RSA)* and the *baroreflex*.

RSA (respiratory sinus arrhythmia) is a physiological phenomenon that creates variability between R-R intervals, causing the heart rate to oscillate in time with the respiratory cycle [2]. These heart rate oscillations occur at the same frequency as our breathing cycle, which is typically between 0.15 and 0.4 Hz for healthy people measured at rest (i.e., 9 - 24 breaths per minute) [42]. However, the RSA phenomenon will always occur in line with the breath[3], so the frequency of this phenomenon will change anytime breathing is volitionally altered, such as during guided breathing exercises [5]. While the exact function of RSA is debated, the effect is widely thought to be an evolutionary adaptation that modulates the heart rate to balance efficient O_2 - CO_2 exchange with overall energy conservation in the body [39]. During each inhale, oxygen-rich fuel enters the body and the heart rate increases to circulate as much blood through the lungs as possible, taking full advantage while the usable fuel is present. When the fuel becomes spent and we begin to exhale, the heart rate decreases to conserve energy until new fuel begins to enter the body at the start of the next breathing cycle.

The *baroreflex* is another physiological phenomenon that contributes to R-R variability [39]. Nervous tissue in the walls of arteries are sensitive to stretch, and these nerves – the baroreceptors – detect changes in blood pressure (since the arteries expand like a balloon when blood is under greater pressure). The baroreflex responds to these changes in pressure and regulates the heart rate to maintain a consistent pressure (i.e., the baroreflex is a negative feedback loop). The baroreflex oscillates because these changes in heart rate are not instantaneously reflected in blood pressure, but instead take time to propagate throughout the circulatory system. The exact frequency at which this oscillation occurs varies from person to person (mainly due to differences in blood volume) but is approximately 0.1 Hz (or ten second breathing cycles) in healthy individuals [24,49].

It is important to note that, in addition to RSA and the baroreflex, there are many other physiological phenomena that contribute to HRV. These include thermoregulation, hormonal processes, and circadian rhythm [42]. However, these phenomena occur over longer time scales (e.g., minutes, hours, days) and do not relate directly / immediately to the acute effects breathing and will therefore not be discussed in detail in this primer.

9 Measuring Autonomic State with HRV: Vagal Tone

Autonomic state is of particular interest when investigating guided breathing because many of the promised benefits of the exercises are based on the notion of affecting balance in our autonomic nervous system. The idea is that, when subjected to chronic stressors, we become out of balance (i.e., we enter a state of sympathetic

[3] Under careful inspection, the phase angle between respiration and RSA is only 0 degrees at an individual's resonance frequency breathing rate, with HRV oscillations slightly trailing or leading respiration at breathing rates above or below resonance frequency, respectively [12,48].

dominance), and guided deep breathing offers an opportunity to boost parasympathetic activity, realigning and restoring homeostasis in the ANS. Since measuring the ANS directly is infeasible in most situations, many researchers have used HRV as an indirect measure of autonomic state. In this section, we explain how HRV can be used for these purposes, specifically highlighting the importance of a measure known as *vagal tone*.

Earlier (in section 2.6), we explained that frequency-domain measures of HRV can be used to decompose an HRV signal and identify the various physiological processes that contribute to it. In addition to the RSA and baroreflex phenomena discussed so far, autonomic state also influences these frequency-based measures of HRV. In fact, the LF:HF ratio (i.e., the ratio of power between the low frequency and high frequency HRV bands) is often used in research as a measure of autonomic balance under the presumption that sympathetic activity in the ANS materializes as low frequency HRV, while parasympathetic activity corresponds to high frequency power [17,30]. However, there is strong evidence that this simplified view does not provide a reliable, accurate, or appropriate representation of autonomic balance [3], and specifically, while there is evidence that the low frequency-to-sympathetic connection is an oversimplification [3], research suggests that high frequency power does provide reliable insight into parasympathetic activity. Therefore, a measure called *vagal tone* – the natural log of high frequency power – is considered to be a more reliable measure of autonomic balance[4]. Beyond the ANS, vagal tone has also been shown to be an measure of health more generally (i.e., beyond the ANS) [16,20,35,36]. Furthermore, since RMSSD has been shown to have high correlation with vagal tone [43] and is less sophisticated to calculate in real time, it is also often used for these purposes. While reliable insight into the *sympathetic* branch of the ANS is thought to be possible using the *pre-ejection period* metric [28], this is a more sophisticated measure that can only be computed from a full ECG recording.

10 Measuring Autonomic State becomes Complex during Guided Breathing

Using HRV as a measure of autonomic state when studying guided breathing exercises comes with several additional caveats. This is because the interpretation of frequency domain HRV measures used to compute vagal tone are based on the assumption that recording were captured while breathing at a natural, unaltered breathing rate [43]. However, volitionally altering the breathing rate influences the effects of RSA on HRV, making it much more difficult to infer autonomic state from the HRV signal [32,43].

In this remainder of this section, we discuss the complexities that arise between breath, HRV, and autonomic state, and identify solutions that have been proposed for these issues.

Breathing Rate Affects HRV – First and foremost, monitoring autonomic state using HRV during guided breathing exercises is difficult because *our breathing rate directly influences our HRV*. As explained in section 2.7 above, the respiratiory sinus arrhymithia (RSA) phenomenon causes heart rate to increase with each inhale and decrease with each exhale. As a consequence, breathing at a different rate will naturally have an influence on HRV measurements, regardless of the HRV metric in question. This is why in many studies that use HRV as a baseline measure of general health, participant's breathing rates are controlled at a consistent rate when HRV measurements are taken [6,20]. In these types of studies the researchers are interested in testing for changes in HRV scores over the course of weeks or even months, so they want to avoid any noise that could be introduced into their measurements due to differences in breathing rates between measurements[5]. For the same reason, many other aspects of the measurements are also controlled in these scenarios (e.g., measurement are taken consistently while seated or laying down, at rest for at least 10 minutes prior to measurement, at a certain period of time following food intake or vigorous exercise).

Monitoring HRV vs. Influencing HRV – What differentiates guided breathing exercises from the scenario just described is that rather than strictly monitoring HRV, the *goal of guided breathing exercises is to have a direct and immediate influence on it*. Even though breathing is altered from the natural resting breathing rate in both monitoring scenario described above as well as in the guided breathing exercises performed in our study, the difference is that guided breathing exercises are designed specifically to exploit the resonance between the

[4] Technically, vagal tone is only a measure of *parasympathetic* activity, not *autonomic balance* overall. However, since so many of us (in Western culture) experience a chronic high-sympathetic and low-parasympathetic imbalance, increases in vagal tone (i.e., parasympathetic activity) can be interpreted as a correction back toward ANS balance.

[5] Obtaining an accurate measure of HRV in these situations can become even more nuanced because naturally occurring changes in resting breathing rate can also indicate a shift in autonomic state, with slower resting breathing rate corresponds to higher vagal tone. If measurements are taken at a consistent paced breathing rate throughout time, any such changes in natural breathing rate could be overlooked.

RSA and the baroreflex that amplifies HRV in real time. With continued practice sustained over weeks or months, guided breathing may have a measurable effect on baseline measurements of HRV collected in a controlled fashion, just as described above (in fact, this has previously been shown to be the case [47]). However, the short-term goal of guided breathing – and the mechanism of particular interest in this experiment – is the coherence between the breath and heart that amplifies HRV. This is why we observed (and expected to observe) an acute effect on HRV in both guided breathing exercises performed in the study.

Real time shifts don't necessarily indicate a change in state – Importantly, the immediate and dramatic increase in HRV created during guided breathing does not necessarily indicate an immediate shift in autonomic state. Since the resonance effect created while in a state of coherence occurs independently from the autonomic nervous system, care must be taken when interpreting the changes in HRV that occur during periods of guided breathing. For example, the fact that we observed increases in SDNN and RMSSD scores in our experiment during the period of time when participant's were performing their breathing exercise is likely a direct result of physiological coherence and not necessarily an indication of an autonomic shift per se. However, sustaining this state of coherence and elevated HRV can influence autonomic state and, in fact, the changes in RMSSD and vagal tone that we observed in participants even after they had completed the breathing exercises (i.e., once their breathing had returned to a natural rate) is more indicitive of such an autonomic shift.

Additional Physiological Markers of Autonomic Shift – All of this complication and contention related to the use of HRV as a measure of autonomic state demonstrates that care must be taken when collecting and interpreting these data. Luckily, there are many other physiological markers of autonomic state that can also be easily measured. In fact, this is what motivated us to capture meaures like peripheral vision and Stroop test performance in our experiment. Even though there are pitfalls and short comings associated with the use of HRV as a measure of autonomic state in isolation, when HRV is considered in combination with other physiological measures it can provide supporting evidence about the underlying behavior of the autonomic nervous system.

11 Coherence and Coherent Breathing – The Goal of Breathing Exercise

Coherence, in general, is a phenomenon that occurs when two or more oscillating processes align with one another or, in other words, *resonate*[6]. This alignment creates a *resonance effect*, or amplification, above and beyond the sum of the effects of each process independently. One dramatic example of this effect is when a singer breaks a crystal glass by sustaining a specific note. In this example, coherence is achieved between the frequency of the auditory pressure waves and the properties of the crystal that the glass is made from, amplifying the vibrations within the glass until they become large enough to cause it to shatter.

Coherent breathing is a synchronization between the RSA effect caused during breathing and the effects of the other internal systems that influence HRV [24,26,44]. Typically, coherent breathing focuses on aligning the breathing with the baroreflex, and when these systems become synchronized their effects resonate, which amplifies the total heart rate variability (again, above and beyond the sum of the effects of the two systems independently). This amplification often occurs quite rapidly and noticeably once a state of coherence is achieved (see Figure 2, which depicts the change in one's heart rate wave when transitioning to a state of coherence). However, unlike the coherence that shatters crystal glass, the amplification in HRV achieved during coherent breathing is desirable and considered to be healthy . With continued practice, coherent breathing can lead to many health benefits [18,25,26]. For example, spending time in this state of amplified HRV has been shown to lead to lowered blood pressure in individuals with hypertension [41], to be an effective treatment for stress and anxiety [19], has increased resistance to relapse in depression [8], has been used as an effective supplement to substance dependence treatments [15], and has even increased cognitive executive functioning [37,38,45,46].Coherence is achieved by reducing the breathing rate to align with the baroreflex, which occurs at approximately 0.1 Hz, or 6 breaths per minute, but varies from person to person due to differences in individual baroreflex response and sensitivity (see above). Due to the resonance effect accompanying coherence, this breathing rate has commonly been referred to as one's "*resonant frequency*" breathing rate [24,25,38,44,45].

[6] https://en.wikipedia.org/wiki/Resonance

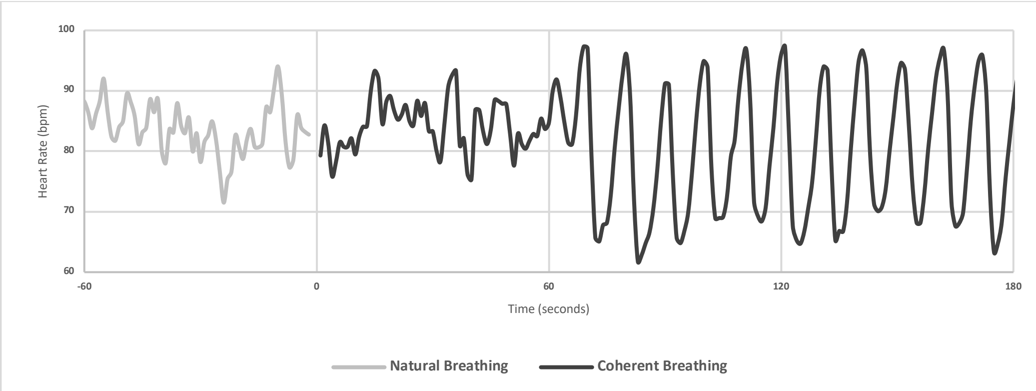

Figure 2: A representative heart rate wave depicting beat-to-beat heart rate during natural breathing (grey) and a coherent breathing exercise (black). Notice that, due to the resonance effect between the breath and baroreflex, the heart rate wave increases in amplitude and becomes more regular during the coherent breathing exercise.

12 Assessing Coherence

During the guided breathing exercises performed in our study, we quantified coherence using a frequency-based analysis of the participant's HRV signal. Specifically, coherence is defined as the percent of the HRV signal's total power concentrated at the breathing rate (as defined in [51]):

$$coherence = (power_{resp} / power_{total}) * 100\%$$

It's worth noting that, based on this definition of coherence, any rhythmic, regular, and consistent breathing rate will raise levels of coherence because it concentrates the effects of RSA at a single frequency; however, only breathing at one's resonance frequency will maximize measured coherence because this breathing rate leads to resonance between the patterns the RSA and baroreflex.

13 Guided Breathing Exercises used to Achieve Coherence: Heart Rate Variability Biofeedback (HRV-b) and Paced Breathing

In our study, we focused on two specific guided breathing exercises that help users reach a state of coherence: *Heart Rate Variability Biofeedback (HRV-b)*, and *paced breathing.* We were interested in whether the exercises differed in their abilities to help guide participants to a state of coherence.

Heart Rate Variability Biofeedback (HRV-b) is designed to help users regulate their breathing relative to their heart rate to achieve coherence. In HRV-b, the goal is to align inhalations and exhalations with the natural rise and fall of changes in the heart-rate. To achieve this, some form of sensor must be worn to monitor heart beats and calculate the heart-rate with each beat. The heart rate is typically plotted and displayed on a screen (although, other visualizations are possible and available in the commercial systems described below) that practicers try to align their breath with (see Figure 3).

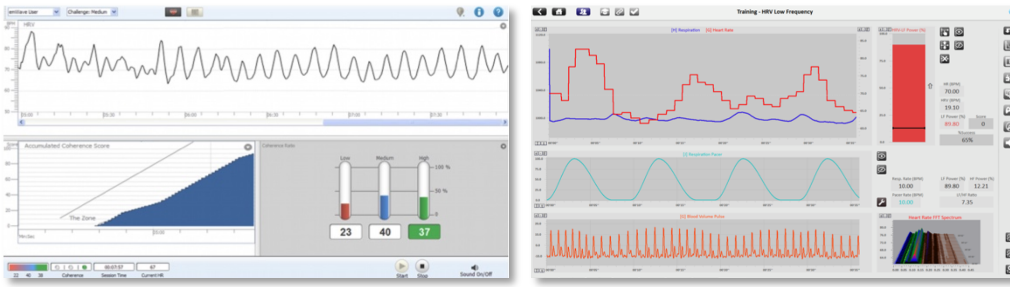

Figure 3: Two commercially available HRV-b products. HeartMath's EmWave (left) and MindMedia's BioTrace+ (right). These examples demonstrate what a user might see during a clinical application of HRV-b. The goal of the exercises is 1) to align the breathing and heart rate wave (the red and blue curves in the top graph of the BioTrace system), 2) maximize the amplitude of the heart rate wave, and 3) concentrate the full HRV power at a single peak (fill the green bar in the bottom-right of the Emwave window, or increase the green spike in the bottom-right plot of the BioTrace window).

Previous research has focused largely on the long term benefits of HRV-b. For example, previous studies have demonstrated that continued practice of HRV-b (over a period of up to eight weeks) can be an effective treatment for hypertension [41]; stress and anxiety [11,22]; relapses in symptoms of depression [8] or substance dependence [15]; and even for improving cognitive performance [13,38,45]. Furthermore, recent studies have uncovered that the early markers of these benefits occur with much less practice, in as little as a single ten-minute HRV-b exercise [10,37,44].

Since HRV-b provides customized feedback to users in real-time, practicing the exercise requires the use of a physiological sensor that monitors HRV. In commercial products like the EmWave and BioTrace+ (Figure 3) this is done with a ear clip, but has recently been demonstrated to be achievable by holding one's finger against a smartphone camera [1,34].

Paced breathing is a simpler approach for approximating the synchronization between the breath and the baroreflex without the use of sensors or real-time feedback. In a paced breathing exercise, an external cue (such as an animation) is typically used as a cue to follow for length and timing of inhalation and exhalation. However, unlike HRV-b, this cue is not derived from the user's physiology or HRV in real-time, so no sensing technology is required. Furthermore, simple pacing cues have the additional benefit of being easy to follow, even when actively focused on something else. For example, recent work has shown that people can accurately match their breathing rate to the rise and fall of a transparent bar on a computer monitor while performing work tasks like manipulating a spreadsheet [31]. Previous work has suggested that paced breathing exercises should target a breathing rate of approximately six breaths per minute, since this is the average resonance frequency breathing rate across individuals.

While paced breathing may be simpler HRV-b, theoretically, only HRV-b provides the information necessary, and therefore, the opportunity to reach a complete state of coherence (i.e., a precise alignment between the breath and the baroreflex). Alternatively, since the exact resonance frequency varies from person to person, it is possible that simple paced breathing at a constant 6 breaths per minute only achieves an approximate state of coherence (i.e., an approximate alignment between the breath and the baroreflex).

14 Our Breath Influences our Body More Generally

Throughout this primer, we have emphasized the relationship between our breath and autonomic state. The key take-away is that *by changing the way we breathe, we influence our autonomic state more generally*. This can have wide reaching effects because the ANS is connected to almost every other system in our body, as illustrated by the numerous health benefits that have been linked to guided breathing exercises [18]. Importantly, HCI plays a critical role in the evolution of guided breathing technologies that faciliate these exercises because we can bring a unique, design-centered approach to these research problems and challenges. Furthermore, this deep-dive into the physiology of breathing has uncovered valuable design knowledge to support the design of technology that leverages and values our natural physiology.

15 Conclusion

Since our breath both affects and is affected by our bodily state more generally, it serves simultaneously as both a marker of physiological state as well as a tool that can in turn be used to influence and tune that physiological state. For designers in general, this means that gaining an awareness of the ways in which their designs influence a user's breathing is critical because it will ultimately play a role in the user's performance, success, and overall experience while interacting with the design (whether intentional or unintentional).

In this primer, we have outlined basic respiratory physiology, focusing on how this knowledge influences the design of technology-mediated guided breathing exercises as well as digital design more broadly. We have synthesized this knowledge in anticipation that it will serve as a valuable resource for HCI researchers and designers pursuing interests in breathing, HRV, or autonomic state in the future; as well as acting as a template for HCI researchers with interests and knowledge in other areas of human physiology.

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