Leveraging Vagally-mediated Heart-rate Variability as an Actionable, Non-invasive Biomarker for Self-regulation: Assessment, Intervention, Evaluation

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Abstract (150 words)

This contribution highlights the significance of using vagally-mediated heart rate variability (vmHRV), a general indicator of adaptation, as an actionable biomarker to assess and enhance self-regulation abilities in individuals and organizations. The paper reviews the state-of-the-art on vmHRV and introduces various techniques to enhance vmHRV, including slow-paced breathing, the diving reflex, transcutaneous vagus nerve stimulation (tVNS), transcranial magnetic stimulation (TMS), and transcranial direct-current stimulation (tDCS). The recommendations for policymaking are based on recent systematic reviews and meta-analyses related to the implementation of these techniques in diverse settings, such as clinical, organizational, and educational contexts. The discussion emphasizes the efficacy, accessibility, and cost-effectiveness of vmHRV assessments, and offers practical tools for individuals and organizations through a three-part framework— assessment, intervention, and evaluation—ultimately fostering self-regulation abilities at both individual and societal levels.

Social media post (280 characters)

Exploring vagally-mediated heart rate variability as a non-invasive biomarker for self-regulation, considering its implications for policymaking across education, healthcare, and organizational settings. A promising tool for understanding and enhancing self-regulation phenomena.

4-6 bulleted highlights of 2-3 lines each

- Vagally-mediated heart rate variability (vmHRV) is a non-invasive biomarker for self-regulation, providing valuable insights into health, work-related stress, cognition, emotion regulation, social interactions, and athletic performance.
- vmHRV can inform policymaking across various domains, including education, healthcare, and organizational settings, by providing data-driven evaluations of initiatives and identifying areas for improvement.

- Slow-paced breathing (SPB) emerges as the most acceptable, scalable and cost-effective intervention for enhancing vmHRV, and should be the main focus of action for policymakers to develop training programs tailored to various audiences and settings
- The use of vmHRV in public health policy can improve health outcomes and promote well-being.
- In occupational settings, vmHRV measurements can identify individuals at risk of stress, fatigue, and burnout. Implementing vmHRV-enhancing techniques can support the improvement of self-regulation skills and overall well-being.
- vmHRV not only provides a tool for understanding self-regulation phenomena but also offers actionable insights for interventions, enhancing the capacity for self-regulation.

Introduction

As the saying goes, "What gets measured gets managed." What if psychological science had a non-invasive indicator that could shed light on the way people regulate their thoughts, emotions, and behaviors? This paper introduces vagally-mediated heart rate variability (vmHRV) as a promising candidate biomarker for such an indicator, offering a cost-effective and non-invasive approach to assess self-regulation across various domains. Exploring the potential of vmHRV for policymakers aims to underscore its utility in improving diverse aspects of self-regulation, such as physical and mental health, social interactions, well-being, and performance.

Vagally-mediated Heart Rate Variability: What This Is, and Why It Matters for Self-regulation

At first glance, one might assume that the interval between successive heartbeats is a fixed, predictable value, such as one second when the heart beats at 60 cycles per minute. In fact, the time interval between successive heartbeats changes constantly, and this phenomenon is known as heart rate variability (HRV) (Laborde, Mosley, & Thayer, 2017; Malik, 1996). This intrinsic variability in heart rate is not to be confused with arrhythmias, which can pose health risks. Rather, it is considered a sign of healthy autonomic nervous system functioning. As aptly summarized by Shaffer, McCraty, and Zerr (2014), a healthy heart is not a metronome.

Vagally-mediated heart-rate variability (vmHRV) originates from increased activity of the vagus nerve (the most prominent nerve of the parasympathetic nervous system - PNS). Along with HRV, vmHRV has emerged as a valuable indicator of adaptation and self-regulation capacity. The neurovisceral integration model (Thayer, Hansen, Saus-Rose, & Johnsen, 2009) posits that vmHRV provides insight into PNS regulating cardiac functioning. In particular, the neurovisceral integration model specifies that resting vmHRV is related to activity in brain regions associated with self-regulation and adaptation processes, and as such is positively associated with a range of phenomena related to self-regulation, adaptation, and health. Building on the neurovisceral integration model, the vagal tank theory (Laborde, Mosley, & Mertgen, 2018b) goes beyond resting vmHRV measurements, to consider the reactivity to specific events, as well as the recovery from those events, which together constitute the three Rs of cardiac vagal functioning (Resting, Reactivity, Recovery). Altogether, the vagal tank theory acknowledges that vmHRV is a dynamic parameter that fluctuates in response to individual and environmental demands. Based on these theoretical considerations, the next section reviews some self-regulation phenomena associated with vmHRV.

VmHRV and Self-regulation Phenomena

The vagus nerve serves as a pivotal pathway to transmit information from the body (e.g., cardiac, endocrine, immune functions) to the brain and vice versa, promoting an optimal distribution of autonomic, metabolic and immunological resources (Bonaz, Sinniger, & Pellissier, 2017). Consistent with the proposed critical role of the vagus nerve in self-regulation (Thayer et al., 2009), vmHRV is associated with a wide range of self-regulatory phenomena. A thorough assessment of the existing evidence, next, primarily relies on summary research articles, such as systematic reviews and meta-analyses. Several key pillars may hold relevance for policymaking:

- **Health.** The vmHRV is associated with a range of health-related phenomena, such as cardiovascular disease (Hillebrand et al., 2013), diabetes (Benichou et al., 2018), hypertension (Queiroz et al., 2022), immunosuppression (McIntosh, 2016), inflammatory markers (Williams et al., 2019), mortality risk (Jarczok et al., 2022), pain (Forte, Troisi, Pazzaglia, Pascalis, & Casagrande, 2022), sleep quality (Chouchou & Desseilles, 2014), and stress regulation (Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012). Regarding the COVID-19 pandemic, vmHRV may be a relevant health marker (Drury, Jarczok, Owens, & Thayer, 2021).
- **Clinical settings**. A low vmHRV has been associated with a range of disorders: anxiety, depression, and panic disorders (Z. Wang et al., 2023), autism (Cheng, Huang, & Huang, 2020), dementia and neurocognitive disorders (Cheng, Huang, & Huang, 2022), emotion dysregulation and psychopathology (Beauchaine & Thayer, 2015), post-traumatic stress disorder (PTSD) (Schneider & Schwerdtfeger, 2020), neurodegenerative

diseases (Liu, Elliott, Knowles, & Howard, 2022), and substance use disorders (Moon, Schlenk, & Lee, 2023).

- **Work-related stress**. More stressful working environments have been associated with reduced vmHRV (Jarvelin-Pasanen, Sinikallio, & Tarvainen, 2018). Likewise, exposure to physical and chemical environments (e.g., exposure to toxicants) as well as shift-based schedules are particularly associated with lower vmHRV (Togo & Takahashi, 2009).
- **Cognition:** The vmHRV has been related positively to executive functioning (Magnon et al., 2022) and to top-down functioning (Holzman & Bridgett, 2017)
- **Emotion regulation.** The vmHRV has been associated positively to effective emotion regulation (Balzarotti, Biassoni, Colombo, & Ciceri, 2017).
- **Social interactions/Aggression/Conflicts.** Negative social interactions reduced vmHRV (Smith, Deits-Lebehn, Williams, Baucom, & Uchino, 2020).
- **Athletic performance.** Athletes' vmHRV is used as a marker of fitness level and to monitor training status (Buchheit, 2014), and has also been related to psychological aspects of athletic performance (Mosley & Laborde, 2022).

This brief overview of domains in which vmHRV can serve as a reliable and sensitive index of physiological functioning provides compelling evidence for its potential utility in diverse fields. The remarkable versatility of vmHRV as an objective marker of cardiac vagal activity underscores the promising value of implementing this metric on a larger scale, which could potentially yield valuable insights into the interplay between physiological processes and behavioral outcomes. Readers should be aware that the described findings predominantly refer to data from White persons and that ethnic differences in vmHRV exist (Hill et al., 2015). Other demographic variables such as sex also moderate vmHRV (Koenig & Thayer, 2016), and should thus be considered.

Methodological Considerations

To ensure accurate interpretation of HRV data, it is necessary to adhere to methodological guidelines that have been previously outlined (Laborde et al., 2017; Malik, 1996). Interested readers are referred to these papers for a comprehensive overview of standardization methods. These guidelines stem from research in controlled settings, and it is currently unclear to what extent they can be implemented and are valid for recordings stemming from wearables in daily life. Nonetheless, some key aspects to consider when measuring HRV: the duration of vmHRV measurements, the type of measurement device used, the time of day at which vmHRV measurements are conducted, the appropriate use of norms, and the use of the 3Rs framework (Resting, Reactivity, and Recovery). Details about these key methodological points are provided in Supplementary Material (1).

Enhancing Cardiac Vagal Activity

Different techniques may help to increase vmHRV. The review focuses on those that have received the most attention in research and for which meta-analytic findings are available, that is, slow-paced breathing (SPB) (Laborde, Allen, et al., 2022), the diving reflex (Ackermann et al., 2022), non-invasive brain stimulation (Schmaußer, Hoffmann, Raab, & Laborde, 2022) via transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), and transcutaneous vagus nerve stimulation (tVNS) (Burger, D'Agostini, Verkuil, & Van Diest, 2020). Some current evidence links these techniques to vmHRV.

Slow-paced Breathing and HRV Biofeedback

SPB is a technique that involves voluntarily regulating one's breath at a slower pace, usually reducing the spontaneous breathing frequency (from 12 to 20 cycles per minute) to around 6 cycles per minute (D'Agostini, Claes, Franssen, von Leupoldt, & Van Diest, 2022; Laborde, Allen, et al., 2022). Variations of SPB include common subtypes, being HRV-biofeedback, resonant frequency breathing, diaphragmatic breathing, or simply paced breathing around 6 cpm. SPB is suggested to have a positive influence on the PNS and promote physical and mental health (Laborde, Allen, et al., 2022; Lehrer et al., 2020; Sevoz-Couche & Laborde, 2022; Van Diest et al., 2014).

SPB constitutes the physiological basis of the technique often referred to as HRV biofeedback, which is basically SPB associated to a physiological feedback, such as heart rate, HRV, or respiratory rate (Laborde et al., 2021; Lehrer et al., 2020). So far, no empirical evidence indicates that

SPB with biofeedback offers superior outcomes in terms of vmHRV (Laborde, Allen, et al., 2022; Laborde et al., 2021) or other health-related outcomes (Lehrer et al., 2020), compared to SPB without biofeedback. Using SPB without biofeedback has lower technological requirements, which facilitates broader accessibility. However, biofeedback can potentially enhance compliance by increased self-efficacy perceptions and motivation for sustained practice (Laborde et al., 2021). Therefore, when resources allow, incorporating biofeedback into SPB practices may still be beneficial.

Diving Reflex

The diving reflex is a physiological response that occurs when an individual is exposed to water, particularly when the face is immersed or cooled. This response helps to conserve oxygen and protect the body during submersion in water by eliciting various cardiovascular changes, including increased cardiac vagal activity (Foster & Sheel, 2005). A recent meta-analysis showed that elicitation of the diving reflex may trigger acute increases in vmHRV (Ackermann et al., 2022).

Non-invasive Brain Stimulation

Non-invasive brain stimulation (NIBS) techniques, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), are primarily used to investigate brain function. TMS involves the application of magnetic fields to specific brain regions, temporarily increasing or decreasing their neuronal activity, while tDCS involves the application of weak electrical currents to either increase or attenuate the brain's excitability. In two meta-analyses, non-invasive brain stimulation enhanced vmHRV (Schmaußer et al., 2022), with TMS and stimulation over the dorsolateral prefrontal cortex eliciting larger effects (Makovac et al., 2017).

Transcutaneus Vagus Nerve Stimulation

tVNS is a non-invasive method that involves stimulating either the auricular (taVNS) or cervical branch (tcVNS) of the vagus nerve by a mild electric current applied to the skin (Farmer et al., 2020). This technique has gained interest in basic, translational, and clinical research due to its non-invasive nature, and has been investigated as a potential intervention technique for various neurological and psychiatric disorders. Given that tVNS directly targets the vagus nerve, it has been suggested as a potential mediator of vmHRV (Burger et al., 2020). Although a recent meta-analysis (Wolf, Kuhnel, Teckentrup, Koenig, & Kroemer, 2021) provided strong evidence for no effects of tVNS on vmHRV during rest, the typical negative association between vmHRV and stressful cognitive measures may be reverted during taVNS, indicating a better adaptation to stress (De Smet et al., 2023). These novel findings suggest that the effects of tVNS on vmHRV may be better understood from the vagal tank perspective, this is to say considering not only resting vmHRV, but also vmHRV changes, and open new venues to explore under which circumstances tVNS may help modulate the relationship between vmHRV and health-related outcomes.

Summary of techniques available to enhance vmHRV

Among the techniques discussed, SPB emerges as the most acceptable, readily available and scalable option for both acute and long-term effects on vmHRV (Laborde, Allen, et al., 2022), as well as a range of health-related outcomes (Lehrer et al., 2020). The diving reflex, though accessible, was found so far to primarily offer acute benefits (Ackermann et al., 2022), and long-term effects need to be further investigated. NIBS (Schmaußer et al., 2022) and to some extent tVNS (Burger et al., 2020; Farmer et al., 2020) present promising results in clinical settings, and may help in the treatment of specific medical conditions. More research is however needed before transferring such neurostimulation strategies to clinical practice.

Applying any of these techniques would not replace a healthy lifestyle. A healthy lifestyle already incorporates several key aspects, such as nutrition, sleep, and physical activity that impact vmHRV (Fatisson, Oswald, & Lalonde, 2016; Laborde, Mosley, & Mertgen, 2018a). However, implementing these techniques is likely to boost the effects of a healthy lifestyle.

Summing Up the Scientific Evidence Regarding vmHRV

The current body of theoretical and empirical evidence highlights the relationship between vmHRV, which serves as an indicator of cardiac vagal activity, and self-regulation phenomena across a diverse range of domains, including health, clinical settings, emotion regulation, cognition, and athletic performance. vmHRV is not a static measure and is affected by various factors that are both within and outside of an individual's control (Fatisson et al., 2016; Laborde et al., 2018a). While some of these factors may be attributed to lifestyle decisions, such as diet and physical activity, specific techniques have also been shown to help improve it. This brief overview of the state-of-the-art regarding vmHRV provides a foundation for policymakers to understand its scientific underpinnings. The ensuing section will focus on the prospective policy implications which may arise by considering this measure.

Policy Implications

Framework: Assessment, Intervention, Evaluation

Recent developments in technology allow measuring vmHRV in a non-invasive and cost-effective manner (Laborde et al., 2017; Stone et al., 2021), making it an attractive tool for policymakers to consider for large-scale implementations. This section will explore the potential policy implications of vmHRV, and how it can contribute to improving overall self-regulation outcomes.

The framework for policy implications based on vmHRV measurement can be structured around three pillars: Assessment, Intervention, and Evaluation (AIE). The vmHRV-AIE framework emphasizes the importance of understanding individuals' self-regulation capacities, as indexed with vmHRV, implementing targeted strategies, and evaluating the effectiveness of these strategies, making it relevant and actionable for policymakers, using for this a goal-oriented and iterative approach.

Assessment

Assessment allows making individuals aware of the impact of lifestyle and other factors on their autonomic nervous system, specifically the parasympathetic branch via vmHRV measurement (Laborde et al., 2017; Malik, 1996). Increasing awareness of vmHRV measurement as a potential biomarker for health and well-being may lead to increased demand for access to such measurements, which can be facilitated by technological developments such as smartphone apps and wearables.

Intervention

Intervention involves promoting the development of activities that enhance vmHRV. Cost-effective, non-pharmacological techniques such as SPB have effectively enhanced vmHRV (Laborde, Allen, et al., 2022), and these can be easily integrated into daily life, such as being implemented before, during, or after stressful events (Laborde, Allen, et al., 2022) – as a Just-in-the-Moment Adaptive Intervention (L. Wang & Miller, 2020); or as an evening routine before going to sleep (e.g., Laborde, Hosang, Mosley, & Dosseville, 2019). Encouraging the adoption of such techniques may improve health outcomes and self-regulation abilities.

Evaluation

Regular vmHRV monitoring via smartphone apps and wearables can provide feedback to individuals on the effectiveness of interventions targeting vmHRV and motivate them to continue engaging in behaviors supporting vmHRV enhancement. The evaluation phase will also enable policymakers to assess the effectiveness of vmHRV-based interventions and policies implemented in various contexts. By analyzing data collected through vmHRV monitoring, policymakers can gain insights into the outcomes of their initiatives, identifying areas of success and areas for improvement. This data-driven evaluation process allows for evidence-based decision-making, as well as the refinement of policies to better support individuals in enhancing their self-regulation abilities.

Application contexts and policy recommendations

Overall, the vmHRV-AIE framework for policy implications aims to leverage the accessibility and non-invasiveness of vmHRV to promote self-awareness, healthy behaviors, and overall well-being. Some areas seem of particular interest for policymakers to support the investigation and implementation of vmHRV.

Supporting Public Health

Incorporating vmHRV measurement into public health policy may improve health outcomes and promote well-being across various domains. Using the vmHRV-AIE framework, policymakers can design effective strategies leveraging vmHRV measurement for public health goals.

• **Assessment:** vmHRV could significantly impact public health campaigns promoting healthy behaviors, physical activity, and reducing substance use disorders. Home-based vmHRV measurements and smartphone apps can help monitor vmHRV as a vital health parameter. Additionally, vmHRV measurement may help to detect early stages of COVID-19 infection and other infectious diseases.

• **Intervention:** Among techniques enhancing vmHRV, SPB is a cost-effective, noninvasive therapy, being potentially the most scalable vmHRV-enhancing technique. Consequently, policies targeting vmHRV enhancement through SPB can support public health initiatives that reach a wide range of people.

• **Evaluation**: Regular vmHRV monitoring via smartphone apps and wearables provides feedback on intervention effectiveness and motivates engagement in healthy behaviors supporting vmHRV enhancement. Evaluating vmHRV-enhancing interventions' impact on public health allows policymakers to refine strategies promoting better health outcomes and overall well-being.

Promoting Well-being in Occupational Settings

The use of vmHRV to support well-being in occupational settings has important policy implications. It is conceivable that in many organizational settings, vmHRV monitoring could become a regular part of health assessments. This could be particularly useful in high-stress professions such as medicine, law enforcement, and the military, where the detection of physical and mental fatigue states may be critical for ensuring public safety. Introducing a vmHRV-AIE framework model to organizations could go beyond health and target employee productivity and well-being at work.

- **Assessment:** vmHRV measurements can identify individuals at risk of stress, fatigue, and burnout. By evaluating vmHRV, organizations can gain insights into employees' self-regulation capacity, allowing for the development of targeted interventions and strategies to address specific vulnerabilities. However, note that the use of such personal health data raises ethical and legal concerns. These include issues of privacy, informed consent, and potential misuse of information. Therefore, any application of vmHRV assessments in organizational settings must be accompanied by robust safeguards to protect individual rights and adhere to legal standards.

- **Intervention:** Implementing vmHRV-enhancing techniques such as SPB can improve self-regulation skills and overall well-being. These techniques can be incorporated into workplace health programs and may help enhance social interactions through appropriate emotion regulation and enhanced cognitive performance.
- **Evaluation:** Regular vmHRV monitoring allows organizations to track changes in employees' health, well-being, productivity, and safety over time. By providing real-time feedback on self-regulation abilities, it encourages proactive stress management and timely interventions, ensuring that employees maintain a healthy work-life balance and minimize the risk of burnout.

Fostering Self-regulation in Educational Environments

Within the educational environment, the application of the vmHRV-AIE framework holds significant promise for fostering self-regulation skills and promoting well-being across all levels of education, from schools to high schools and universities. This comprehensive approach emphasizes the assessment of students' self-regulation capacities, the implementation of targeted interventions, and the ongoing evaluation of outcomes.

- **Assessment:** vmHRV measurements can provide valuable insights into students' self-regulation capacities. By incorporating vmHRV as a tool for assessment, educational institutions can gain a better understanding of students' physiological responses to stress and their overall self-regulation abilities. This assessment serves as a foundation for targeted interventions and support strategies tailored to individual student needs.
- **Interventions:** In schools, introducing vmHRV as a tool for teaching early relaxation methods can be integrated into the curriculum. By incorporating age-appropriate smartphone apps and

devices, schools can provide practical tools for self-regulation, promoting healthy habits that extend into adolescence and adulthood. In high schools and universities, where students face increased academic pressures and stress, it is vital that educational institutions equip students with the skills and knowledge to effectively manage stress, regulate their emotions, and maintain a healthy balance in their academic and personal lives.

- **Evaluation**: By systematically evaluating the outcomes of vmHRV-based interventions and measuring their impact on students' self-regulation and well-being, educational institutions can refine their approaches, identify areas for improvement, and make evidence-based decisions to optimize students' growth and development.

Facilitating Mental Health Care and Therapy

The application of the vmHRV-AIE framework in mental health care and therapy can significantly enhance the management and treatment of various mental conditions. It can also facilitate a more comprehensive and personalized approach to treatment, improving patient outcomes and overall mental well-being.

- **Assessment:** vmHRV measurements can be used as a complementary tool to assess individuals at risk for mental health issues, such as anxiety, depression, and PTSD. By evaluating baseline vmHRV levels, clinicians can gain insights into an individual's self-regulation capacity. This information can guide the development of personalized treatment plans tailored to the individual's specific needs.
- **Intervention:** Incorporating vmHRV-enhancing techniques into mental health treatment plans can improve patients' self-regulation capacities. These techniques can augment traditional therapeutic approaches, such as cognitive-behavioral therapy, enhancing their effectiveness and promoting long-term mental health improvements.
- **Evaluation:** Regular vmHRV monitoring can be employed to track patients' progress throughout the course of therapy. By evaluating changes in vmHRV, therapists can assess the effectiveness of interventions and make necessary adjustments to treatment plans. As vmHRV is a

non-invasive and relatively simple measure, patients can easily incorporate it into their daily routine, providing real-time feedback on their self-regulation abilities and overall well-being.

Assisting Older Adults and Geriatric Care

The application of the vmHRV-AIE framework in geriatric care can greatly support the well-being of older adults, addressing age-related challenges and promoting a healthier aging process.

- **Assessment:** vmHRV measurements in older adults can serve as a tool to identify those potentially at a higher risk of age-related health issues, such as cognitive decline, cardiovascular diseases, and frailty. By evaluating vmHRV, healthcare providers can gain insights into an individual's self-regulation capacity. This knowledge allows for the development of targeted intervention strategies to address specific vulnerabilities.
- **Intervention:** Implementing vmHRV-enhancing techniques can support the maintenance and improvement of self-regulation capacities in older adults. These interventions can be tailored to individual needs and incorporated into existing geriatric care plans, helping to mitigate age-related health issues and foster overall well-being.
- **Evaluation:** Regular vmHRV monitoring enables healthcare professionals to track changes in the self-regulation abilities and overall health status of older adults over time. This facilitates early detection of potential health concerns and promotes timely interventions. Regularly assessing vmHRV can obtain a dynamic picture of an elderly individual's health status, reducing the risk of adverse outcomes and enhancing the quality of life for the elderly population.

Strategies for Implementation

Campaign to Encourage vmHRV Monitoring Becoming a Habit

Measuring vmHRV could be implemented as a habit in daily life to provide awareness about the functioning of the autonomic nervous system, just as athletes monitor their training status (Altini & Plews, 2021). Just as brushing teeth is a direct actionable step for dental health, measuring vmHRV could become a habitual practice that promotes health and well-being. By incorporating vmHRV monitoring into health promotion campaigns and public health initiatives, individuals can become more aware of how their behavior (e.g., drinking alcohol, sleeping less) has a direct impact on vmHRV and in maintaining overall health.

Regular evaluation through vmHRV monitoring empowers individuals to track their progress and adjust as needed. By promoting the use of vmHRV monitoring as a habitual practice within the context of a vmHRV-AIE framework, individuals can take an active role in their health and well-being, potentially leading to improved overall health outcomes that would help to decrease the pressure on the overall social health system.

However, consider potential risks and challenges associated with this approach. For instance, the constant monitoring and checking of health data can lead to an unhealthy preoccupation, which can, paradoxically, induce stress and frustration. Misinterpretation of data is another concern, because individuals without proper training or understanding may draw incorrect conclusions about their health status. Furthermore, the use of wearable devices for vmHRV monitoring may inadvertently exacerbate the social gradient in health. These devices, while increasingly popular, are often more accessible to individuals with higher income levels. Additionally, using these devices effectively may challenge individuals with less education. Therefore, while vmHRV monitoring holds promise, it is crucial to ensure that its benefits are accessible and beneficial to all.

Supporting basic and applied research

Governmental agencies should prioritize funding research on vmHRV to facilitate basic research and to ensure the translation into applications that benefit society on a large scale, particularly in the context of the vmHRV-AIE framework. By supporting programs that link universities to companies focusing on the development of new vmHRV measurement technologies, research in vmHRV could lead to the creation of low-cost, yet reliable vmHRV measurement devices. This could have significant implications for the development of innovative technological directions, such as the potential for contactless assessment of vmHRV.

Therefore, government funding for vmHRV research could help promote the development of reliable, low-cost vmHRV measurement technologies, which in turn could create innovative tools to improve health and well-being. By incorporating the vmHRV-AIE framework in conjunction with these new technologies, individuals and organizations can better assess, intervene, and evaluate their self-regulation and stress management efforts.

As such, the funding of vmHRV research could advance health technologies and improve health outcomes for the general population. This investment in vmHRV research, aligned with the vmHRV-AIE framework, could revolutionize the way individuals and organizations approach overall health and well-being.

Conclusion

In conclusion, recent theoretical and empirical developments in HRV research lay the groundwork for establishing recommendations for policy making. However, as Karemaker (2020) reminds us, *"the heart may be the mirror of the soul, but the human mind is more than its heart rate variability."* While vmHRV is only one number and has no value if used in isolation, it can prove to be a valuable adjunct measure within a holistic health approach.

The vmHRV-AIE framework, as presented here, provides a comprehensive, scalable approach based on vmHRV representing a key biomarker for enhancing self-regulation. This endeavor builds on a recent special issue showcasing the use of vmHRV at the horizon 2030 (Laborde, Mosley, Bellenger, & Thayer, 2022), highlighting the diversity of self-regulation phenomena associated with vmHRV, as well as the most recent technological developments in this area and its exciting applications for the future.

The current paper outlined the potential for non-pharmacological techniques to increase vmHRV, such as SPB, the diving response, NIBS, and tVNS. These techniques serve as actionable leverages that policymakers can consider when formulating policies to enhance self-regulation abilities. Among these interventions, SPB distinctly emerges as the most promising, making it a central focus for policymakers. The evidence supporting SPB is increasingly robust, backed by extensive research demonstrating its efficacy in improving vmHRV (Laborde, Allen, et al., 2022) and a large-range of physical and mental health-related outcomes (Lehrer et al., 2020). Healthcare providers, educational institutions, and organizations across various sectors could substantially benefit from integrating SPB into their health programs. The cost/benefit analysis of SPB reveals a promising picture: it requires minimal equipment and training, making it financially accessible, while its benefits in terms of improved self-regulation, health, and well-being are far-reaching. Policymakers should therefore focus on developing accessible training material tailored to various audiences and create programs that encourage stakeholders – including parents, teachers, public health officials, and corporate health coordinators – to actively consider implementing SPB practices.

By thoughtfully considering and implementing the insights provided by vmHRV research within the vmHRV-AIE framework, policymakers can make more informed, evidence-based and data-driven decisions that promote the development of enhanced self-regulation at both the individual and societal levels. To enable a visual understanding of this manuscript, we have provided a complete infographic in Supplementary Material (2).

In sum, these endeavors may help reach the goal of *making the world more parasympathetic*, empowering individuals with enhanced self-regulation abilities to live fulfilling lives, vmHRV becoming an actionable biomarker having the potential to shape a future where self-regulation becomes a cornerstone of personal and societal flourishing.

References

Ackermann, S. P., Raab, M., Backschat, S., Smith, D. J. C., Javelle, F., & Laborde, S. (2022). The diving response and cardiac vagal activity: A systematic review and meta-analysis. *Psychophysiology*, e14183. doi:10.1111/psyp.14183

Balzarotti, S., Biassoni, F., Colombo, B., & Ciceri, M. R. (2017). Cardiac vagal control as a marker of emotion regulation in healthy adults: A review. *Biol Psychol, 130*, 54-66. doi:10.1016/j.biopsycho.2017.10.008

Beauchaine, T. P., & Thayer, J. F. (2015). Heart rate variability as a transdiagnostic biomarker of psychopathology. *International Journal of Psychophysiology, 98*(2 Pt 2), 338-350. doi:10.1016/j.ijpsycho.2015.08.004

Benichou, T., Pereira, B., Mermillod, M., Tauveron, I., Pfabigan, D., Maqdasy, S., & Dutheil, F. (2018). Heart rate variability in type 2 diabetes mellitus: A systematic review and meta-analysis. *PLoS ONE, 13*(4), e0195166. doi:10.1371/journal.pone.0195166

Bonaz, B., Sinniger, V., & Pellissier, S. (2017). The Vagus Nerve in the Neuro-Immune Axis: Implications in the Pathology of the Gastrointestinal Tract. *Front Immunol, 8*, 1452. doi:10.3389/fimmu.2017.01452

Buchheit, M. (2014). Monitoring training status with HR measures: do all roads lead to Rome? *Front Physiol, 5*, 73. doi:10.3389/fphys.2014.00073

Burger, A. M., D'Agostini, M., Verkuil, B., & Van Diest, I. (2020). Moving beyond belief: A narrative review of potential biomarkers for transcutaneous vagus nerve stimulation. *Psychophysiology, 57*(6), e13571. doi:10.1111/psyp.13571

Cheng, Y. C., Huang, Y. C., & Huang, W. L. (2020). Heart rate variability in individuals with autism spectrum disorders: A meta-analysis. *Neurosci Biobehav Rev, 118*, 463-471. doi:10.1016/j.neubiorev.2020.08.007

Cheng, Y. C., Huang, Y. C., & Huang, W. L. (2022). Heart rate variability in patients with dementia or neurocognitive disorders: A systematic review and meta-analysis. *Aust N Z J Psychiatry, 56*(1), 16-27. doi:10.1177/0004867420976853

Chouchou, F., & Desseilles, M. (2014). Heart rate variability: a tool to explore the sleeping brain? *Frontiers in Neuroscience, 8*, 402. doi:10.3389/fnins.2014.00402

D'Agostini, M., Claes, N., Franssen, M., von Leupoldt, A., & Van Diest, I. (2022). Learn to breathe, breathe to learn? No evidence for effects of slow deep breathing at a 0.1 Hz frequency on reversal learning. *Int J Psychophysiol, 174*, 92-107. doi:10.1016/j.ijpsycho.2022.01.008

De Smet, S., Ottaviani, C., Verkuil, B., Kappen, M., Baeken, C., & Vanderhasselt, M. A. (2023). Effects of non-invasive vagus nerve stimulation on cognitive and autonomic correlates of perseverative cognition. *Psychophysiology, 60*(6), e14250. doi:10.1111/psyp.14250

Drury, R. L., Jarczok, M., Owens, A., & Thayer, J. F. (2021). Wireless Heart Rate Variability in Assessing Community COVID-19. *Front Neurosci, 15*, 564159. doi:10.3389/fnins.2021.564159

Farmer, A. D., Strzelczyk, A., Finisguerra, A., Gourine, A. V., Gharabaghi, A., Hasan, A., . . . Koenig, J. (2020). International Consensus Based Review and Recommendations for Minimum Reporting Standards in Research on Transcutaneous Vagus Nerve Stimulation (Version 2020). *Front Hum Neurosci, 14*, 568051. doi:10.3389/fnhum.2020.568051

Fatisson, J., Oswald, V., & Lalonde, F. (2016). Influence diagram of physiological and environmental factors affecting heart rate variability: an extended literature overview. *Heart International, 11*(1), e32-e40. doi:10.5301/heartint.5000232

Forte, G., Troisi, G., Pazzaglia, M., Pascalis, V., & Casagrande, M. (2022). Heart Rate Variability and Pain: A Systematic Review. *Brain Sci, 12*(2). doi:10.3390/brainsci12020153

Foster, G. E., & Sheel, A. W. (2005). The human diving response, its function, and its control. *Scandinavian Journal of Medicine & Science in Sports, 15*(1), 3-12. doi:10.1111/j.1600-0838.2005.00440.x

Hill, L. K., Hu, D. D., Koenig, J., Sollers, J. J., 3rd, Kapuku, G., Wang, X., . . . Thayer, J. F. (2015). Ethnic differences in resting heart rate variability: a systematic review and meta-analysis. *Psychosom Med, 77*(1), 16-25. doi:10.1097/PSY.0000000000000133

Hillebrand, S., Gast, K. B., de Mutsert, R., Swenne, C. A., Jukema, J. W., Middeldorp, S., . . . Dekkers, O. M. (2013). Heart rate variability and first cardiovascular event in populations without known cardiovascular disease: meta-analysis and dose-response meta-regression. *Europace, 15*(5), 742-749. doi:10.1093/europace/eus341

Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. *Neuroscience & Biobehavioral Reviews, 74*(Pt A), 233-255. doi:10.1016/j.neubiorev.2016.12.032

Jarczok, M. N., Weimer, K., Braun, C., Williams, D. P., Thayer, J. F., Gündel, H. O., & Balint, E. M. (2022). Heart rate variability in the prediction of mortality: A systematic review and meta-analysis of healthy and patient populations. *Neuroscience & Biobehavioral Reviews, 143*. doi:10.1016/j.neubiorev.2022.104907

Jarvelin-Pasanen, S., Sinikallio, S., & Tarvainen, M. P. (2018). Heart rate variability and occupational stress-systematic review. *Ind Health*. doi:10.2486/indhealth.2017-0190

Karemaker, J. M. (2020). Interpretation of Heart Rate Variability: The Art of Looking Through a Keyhole. *Front Neurosci, 14*, 609570. doi:10.3389/fnins.2020.609570

Koenig, J., & Thayer, J. F. (2016). Sex differences in healthy human heart rate variability: A meta-analysis. *Neurosci Biobehav Rev, 64*, 288-310. doi:10.1016/j.neubiorev.2016.03.007

Laborde, S., Allen, M. S., Borges, U., Dosseville, F., Hosang, T. J., Iskra, M., . . . Javelle, F. (2022). Effects of voluntary slow breathing on heart rate and heart rate variability: A systematic review and a meta-analysis. *Neuroscience & Biobehavorial Reviews, 138*, 104711. doi:10.1016/j.neubiorev.2022.104711

Laborde, S., Allen, M. S., Borges, U., Iskra, M., Zammit, N., You, M., . . . Dosseville, F. (2021). Psychophysiological effects of slow-paced breathing at six cycles per minute with or without heart rate variability biofeedback. *Psychophysiology, 59*(1), e13952. doi:10.1111/psyp.13952

Laborde, S., Hosang, T., Mosley, E., & Dosseville, F. (2019). Influence of a 30-day slow paced breathing intervention compared to social media use on subjective sleep quality and cardiac vagal activity. *Journal of Clinical Medicine, 8*(2). doi:10.3390/jcm8020193

Laborde, S., Mosley, E., Bellenger, C. R., & Thayer, J. F. (2022). Editorial: Horizon 2030: Innovative Applications of Heart Rate Variability. *Frontiers in Neuroscience*. doi:10.3389/fnins.2022.937086

Laborde, S., Mosley, E., & Mertgen, A. (2018a). A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon, 4*(12), e01002. doi:10.1016/j.heliyon.2018.e01002

Laborde, S., Mosley, E., & Mertgen, A. (2018b). Vagal Tank Theory: The Three Rs of Cardiac Vagal Control Functioning – Resting, Reactivity, and Recovery. *Frontiers in Neuroscience, 12*. doi:10.3389/fnins.2018.00458

Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart Rate Variability and Cardiac Vagal Tone in Psychophysiological Research - Recommendations for Experiment Planning, Data Analysis, and Data Reporting. *Frontiers in Physiology, 8*, 213. doi:10.3389/fpsyg.2017.00213

Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., & Zhang, Y. (2020). Heart Rate Variability Biofeedback Improves Emotional and Physical Health and Performance: A Systematic Review and Meta Analysis. *Applied Psychophysiology & Biofeedback, 45*(3), 109-129. doi:10.1007/s10484-020-09466-z

Liu, K. Y., Elliott, T., Knowles, M., & Howard, R. (2022). Heart rate variability in relation to cognition and behavior in neurodegenerative diseases: A systematic review and meta-analysis. *Ageing Research Reviews, 73*. doi:10.1016/j.arr.2021.101539

Magnon, V., Vallet, G. T., Benson, A., Mermillod, M., Chausse, P., Lacroix, A., . . . Dutheil, F. (2022). Does heart rate variability predict better executive functioning? A systematic review and meta-analysis. *Cortex, 155*, 218-236. doi:10.1016/j.cortex.2022.07.008

Malik, M. (1996). Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *European Heart Journal, 17*, 354-381.

McIntosh, R. C. (2016). A meta-analysis of HIV and heart rate variability in the era of antiretroviral therapy. *Clin Auton Res, 26*(4), 287-294. doi:10.1007/s10286-016-0366-6

Moon, S. J. E., Schlenk, E. A., & Lee, H. (2023). Heart Rate Variability in Adults With Substance Use Disorder: A Comprehensive Narrative Review. *J Am Psychiatr Nurses Assoc*, 10783903221145142. doi:10.1177/10783903221145142

Mosley, E., & Laborde, S. (2022). A scoping review of heart rate variability in sport and exercise psychology. *International Review of Sport and Exercise Psychology*, 1-75. doi:10.1080/1750984x.2022.2092884

Queiroz, M. G., Prado, A. G. K., Alves-Santos, E. T., Araujo, J. A., Damazo, A. S., & Cambri, L. T. (2022). Influence of family history of hypertension on blood pressure and heart rate variability in young adults: a meta-analysis. *Blood Press Monit, 27*(4), 259-271. doi:10.1097/MBP.0000000000000599

Schmaußer, M., Hoffmann, S., Raab, M., & Laborde, S. (2022). The effects of noninvasive brain stimulation on heart rate and heart rate variability: A systematic review and meta-analysis. *Journal of Neuroscience Research, 100*(9), 1664-1694. doi:10.1002/jnr.25062

Schneider, M., & Schwerdtfeger, A. (2020). Autonomic dysfunction in posttraumatic stress disorder indexed by heart rate variability: a meta-analysis. *Psychol Med, 50*(12), 1937-1948. doi:10.1017/S003329172000207X

Sevoz-Couche, C., & Laborde, S. (2022). Heart rate variability and slow-paced breathing:when coherence meets resonance. *Neuroscience & Biobehavorial Reviews, 135*, 104576. doi:10.1016/j.neubiorev.2022.104576

Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Frontiers in Psychology, 5*, 1040. doi:10.3389/fpsyg.2014.01040

Smith, T. W., Deits-Lebehn, C., Williams, P. G., Baucom, B. R. W., & Uchino, B. N. (2020). Toward a social psychophysiology of vagally mediated heart rate variability: Concepts and methods in self-regulation, emotion, and interpersonal processes. *Social and Personality Psychology Compass, 14*(3). doi:10.1111/spc3.12516

Stone, J. D., Ulman, H. K., Tran, K., Thompson, A. G., Halter, M. D., Ramadan, J. H., . . . Hagen, J. A. (2021). Assessing the Accuracy of Popular Commercial Technologies That Measure Resting Heart Rate and Heart Rate Variability. *Frontiers in Sports and Active Living, 3*. doi:10.3389/fspor.2021.585870

Thayer, J. F., Ahs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews, 36*, 747-756. doi:10.1016/j.neubiorev.2011.11.009

Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine, 37*, 141-153. doi:10.1007/s12160-009-9101-z

Togo, F., & Takahashi, M. (2009). Heart rate variability in occupational health --a systematic review. *Ind Health, 47*(6), 589-602.

Van Diest, I., Verstappen, K., Aubert, A. E., Widjaja, D., Vansteenwegen, D., & Vlemincx, E. (2014). Inhalation/Exhalation ratio modulates the effect of slow breathing on heart rate variability and relaxation. *Applied Psychophysiology & Biofeedback, 39*(3-4), 171-180. doi:10.1007/s10484-014-9253-x

Wang, L., & Miller, L. C. (2020). Just-in-the-Moment Adaptive Interventions (JITAI): A Meta-Analytical Review. *Health Commun, 35*(12), 1531-1544. doi:10.1080/10410236.2019.1652388

Wang, Z., Luo, Y., Zhang, Y., Chen, L., Zou, Y., Xiao, J., . . . Zou, Z. (2023). Heart rate variability in generalized anxiety disorder, major depressive disorder and panic disorder: A network meta-analysis and systematic review. *J Affect Disord, 330*, 259-266. doi:10.1016/j.jad.2023.03.018

Williams, D. P., Koenig, J., Carnevali, L., Sgoifo, A., Jarczok, M. N., Sternberg, E. M., & Thayer, J. F. (2019). Heart rate variability and inflammation: A meta-analysis of human studies. *Brain Behav Immun, 80*, 219-226. doi:10.1016/j.bbi.2019.03.009

Wolf, V., Kuhnel, A., Teckentrup, V., Koenig, J., & Kroemer, N. B. (2021). Does transcutaneous auricular vagus nerve stimulation affect vagally mediated heart rate variability? A living and interactive Bayesian meta-analysis. *Psychophysiology, 58*(11), e13933. doi:10.1111/psyp.13933