Envisioning Ubiquitous Biosignal Interaction with Multimedia

Ekaterina R. Stepanova
KTH Royal Institute of Technology
Stockholm, Sweden
katerina_stepanova@sfu.ca

Alice C. Haynes
KTH Royal Institute of Technology
Stockholm, Sweden
ahaynes@kth.se

Laia Turmo Vidal
KTH Royal Institute of Technology
stockholm, Sweden
laia.turmo@gmail.com

Francesco Chiossi
LMU
Munich, Germany
francesco.chiossi@um.ifi.lmu.de

Abdallah El Ali
Centrum Wiskunde &
Informatica
amsterdam, Netherlands
Abdallah.El.Ali@cwi.nl

Luis Quintero
Stockholm University
Stockhom, Sweden
luis.quintero@dsv.su.se

Yoav Luft
KTH Royal Institute of Technology
Stockholm, Sweden
luft@kth.se

Nadia Campo Woytuk
KTH Royal Institute of Technology
Stockholm, Sweden
Nadiacw@kth.se

Sven Mayer
LMU
Munich, Germany
sven.mayer@ifi.lmu.de

Abstract

Biosensing technologies are on their way to becoming ubiquitous in multimedia interaction. These technologies capture physiological data, such as heart rate, breathing, skin conductance, and brain activity. Researchers are exploring biosensing from perspectives including engineering, design, medicine, mental health, consumer products, and interactive art. These technologies can enhance our interactions, allowing us to connect with our bodies and others around us across diverse application areas. However, the integration of biosignals in HCI presents new challenges pertaining to choosing what data we capture, interpreting these data, its representation, application areas, and ethics. There is a need to synthesize knowledge across diverse perspectives of researchers and designers spanning multiple domains and to map a landscape of the challenges and opportunities of this research area. The goal of this workshop is to exchange knowledge in the research community, introduce novices to this emerging field, and build a future research agenda.

CCS Concepts

• **Human-centered computing** → **Interaction techniques**; **Interaction design theory, concepts and paradigms**.

Keywords

biosignals, physiological signals, biofeedback, biodata, communication, affective computing, ethics, biosignal representation, wearables

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1 Motivation

In Human-Computer Interaction (HCI), biosensing technology is becoming more ubiquitous in multimedia interactions. Consumer devices, e.g., fitness and health trackers, smartwatches, cellphones, and Virtual Reality (VR) headsets, often include sensors that capture our bodily data. Physiological sensors can capture bodily processes, such as heart rate, respiration, skin conductance, brain activity, and eye-tracking. This provides us with **biosignals** and **biodata** that we can use for analysis of user's states, responses, and experience [4], and by extension, adapt systems to their responses [9, 11]. By representing these data to the user, we can offer **biofeedback** to help users learn more about themselves, train their body awareness, and improve their state [25]. Sharing biosignals in social contexts could augment communication and inform group dynamics [28]. Biodata can also offer a design material to designers [1, 16] cultivating the knowledge and appreciation of our bodies and guiding the design process [15].

For example, biodata can give access to a dimension of our experience that ordinarily remains hidden, providing cues indicative of our internal cognitive, affective, and health states [36]. These cues may, for instance, allow for the recognition and training of our attention levels, enable attunement to others' emotions, communication of affective intimate messages, and foster empathy. Moreover, biosignals may help us to learn to recognize these cues in the absence of technology, as well as to identify emotional and cognitive states that may otherwise be completely hidden. It particularly has the potential to aid people with sensory challenges or social disabilities, such as individuals on the autism spectrum [29]. Biosignals may be used for health monitoring, emotion and stress

regulation, attention training, affective communication, appreciation of aesthetic experiences, and improving a feeling of connection. Thus, biosignals may provide important implicit physiological cues obscured not only in face-to-face interactions but also missing from current telepresence and communication technologies, including video conferencing and VR. Biosignal sharing in social contexts is particularly relevant with the recent dominance of telecommunication resulting from the COVID-19 pandemic and the shortage of rich social, affective cues in many of our technology-mediated interactions.

Despite the growing pervasiveness of biosensing technologies, there is a lack of comprehensive design and research frameworks, ethical guidelines, or even a consistent theory and vocabulary around designing with biodata. There is an urgent need to discuss how we *can* and *should* integrate biodata into our HCI research such that we design in ways that improve our lives and minimize ethical risks. Building on our previous workshops on this topic at DIS'23 [39] and CHI'24 [10], we aim to broaden the community of researchers interested in biodata by inviting a wider range of participants with diverse expertise. We will invite not only experts in biosignals to share their insights but also researchers new to this field who are curious about integrating biosignals into their domain. Together, we will map out the landscape of biosensing technologies' research and design field and develop a future research agenda.

2 Workshop Topics

Workshop activities and discussions will span three overarching topics. The activities will help participants to identify and articulate challenges and opportunities offered by biosensing technologies. Through this communal effort, we will begin to map out the emerging research and design landscape of biosensing in multimedia interaction.

TOPIC 1—Interpretation and effects of biodata: Which biosignals do we capture, and how do we interpret them? How do we represent biodata? How may this representation change our experience, behavior, and interpretation of these data? Biodata can offer insights into the processes of our bodies, health, fitness, and cognitive and affective states. However, how we make sense of these signals, both as researchers and as users, can often be ambiguous. From a user's perspective, when we are presented with biofeedback, we can draw diverse interpretations from it, often imbuing it with a deeper meaning that differs among users [17, 26]. For example, what does it mean if my heart rate sped up by 10 beats after entering a room (cf., El Ali et al. [13])? Users can tend to be overly convinced by what biodata is telling them about their feelings, trusting it more than their own subjective experience [18]. But even among researchers, for example, in affective computing, there is a prominent debate about how much we can understand about users' emotions based on their physiological data because of the diversity of physiological expressions and cultural and contextual complexity of emotions [23]. Moreover, different subdomains of HCI treat biosignals substantially differently, putting various values on them, for example, as described by Prpa et al. [31]. For instance, approaches rooted in medicine outline prescriptive optimal breathing rates that promise to deliver desired outcomes, such as relaxation. Soma-design approaches treat biodata as a prompt for directing attention to the felt experience without a direct concern about the exact value presented or trying to optimize it. The place where the interaction happens also shapes the quality and meaning of it. For instance, sharing the heartbeat between people in a romantic relationship over distance may feel like an effective intimate message [24]. However, with both people in the same room, it may feel redundant [38], while in a public space, it may feel vulnerable and inappropriate.

The nuances of the choice of the representation of biofeedback is another challenge. Biosignals can be represented through different modalities, shaping our processing of this representation and how it may affect us. While visual modality is the dominant one [25], other modalities could offer a more compelling embodied experience [41]. We can present raw data, e.g., heartbeats, or aggregate data, e.g., heart rate variability, processed singles interpreted into emotions, stress level or attention levels [14], or abstract and artistic forms such as varying the appearance of an avatar in VR [3] or displaying artificial biosignals [22]. These choices come with trade-offs. The raw data can be challenging to interpret for naive users [38], but processed data, e.g., inferred emotions, can seem less believable to users (e.g., Liu et al. [24]) and require personalized explanations for the emotion detection models (e.g., Quintero et al. [33]) . With multiple users, there are various possibilities for mapping and representing signals for each individual, providing an individual representation, or group aggregate [42], thus reducing privacy concerns [32] as well as deciding whether the representation should be symmetrical across users. The chosen modality, temporality, and display design will greatly impact how users perceive biosignals and how subtle or intrusive they may be within our already occupied attention spans.

TOPIC 2—Application areas: There is a diverse range of explored application areas for integrating biosignals. Biosensing in HCI can offer insights about user experiences, such as understanding their attentional patterns and experience through eye-tracking [2], or for example, their arousal or emotions through heart rate [12, 37]. Biofeedback has been employed to help mitigate stress [6, 44], change participants' perception of their own movement and body [41], train attention for lucid dreaming [20], etc. In the social context, researchers explored supporting intimacy in long-distance relationships [24], fostering empathy and compassion among strangers in VR [34], productivity and feeling human contact in both physical and telepresent workplaces [7, 43], group meditation [27], inviting reflection in public spaces building "smart cities" [19], augmenting social expression through wiggling ears [30], stimulating social exertion in sports [42], or measuring attention [21] to monitor engagement of students in the classroom. Biodata sharing could augment any social interaction to achieve varying effects depending on the application, offering novel support across many aspects of our lives. To ensure we can benefit from this emerging technology, it is important to consider the breadth of possible applications that could bring value to our lives and society. While much of the early development of consumer biosensing applications have been focused on individual health and self-improvement, rooted in the "quantified self" movement, it is important to consider the wider breadth of applications this technology can serve in our society.

TOPIC 3—Ethics of Biosignals: Working with biosignals inevitably raises ethical concerns and considerations due to the highly sensitive nature of the data and the potential for sensing without users' full awareness [8, 35]. These factors are complex and multi-layered, pertaining not only to what data is collected but how it is collected, who by, how it is used, and in what contexts, etc. Physiological data is inherently private and, by extension, should be regarded as sensitive information that requires individual agency regarding its disclosure. However, enabling agency and informed consent is challenging, and we lack best practices for supporting users in understanding what their biodata may reveal about them [18]. For example, much of our biodata is hidden from ourselves in everyday contexts (e.g., EEG signals recording brain activity), and we may not be aware of what this data can reveal. In particular, with data such as EEG, a user may not have the necessary expertise or knowledge to make meaningful interpretations, requiring them to share that data with an expert or external party to understand and make use of it. This external party then not only has access to their data but may be able to infer more sensitive information from the data than the user is aware of. This raises crucial questions of privacy, agency over data, equity and power relationships, data use and storage. Users need to be informed and empowered to understand how their data may be used or interpreted by third parties, and they need to be able to make decisions on how their data is used without compromising their needs. To take a recent example concerning biodata privacy in consumer products, the change in the constitutional right to abortion in the United States in 2022 caused many users of menstrual tracking apps to be concerned about the privacy of their collected data and access to that data by third parties or law enforcement [5]. These apps collect and track highly personal data from which it can be possible to detect or infer abortions. While many users were engaging with the apps for health reasons and fertility tracking, the possibility for third parties to infer highly sensitive details about their lives and bodies, often without giving users adequate ability to personalize their privacy settings, was a serious concern. In this case, many users deleted the app in response to their concern over data privacy. This highlights the power imbalance between service providers and users. Long-term users who have developed a vested interest in a service are vulnerable to changes in data privacy policies that may not align with their expectations or values. A further area of concern is potential inaccuracies of sensor readings, biases in signal processing and predictive modeling, and limits of interpretation of the biodata. Developers must exercise transparency regarding the accuracy and interpretative capabilities of biodata, especially considering sensitive applications such as health monitoring. Engaging with biodata can influence how individuals perceive themselves and their bodies, change their behavior, and even alter other people's perceptions of and interactions with them. Therefore, it is imperative that we, as designers and researchers in HCI, accept responsibility for actively engaging in an ethics dialogue throughout the development of new biosensing technologies. Now is a crucial time to address these ethical concerns. Considering the myriad and complex ethical concerns raised by engaging with biodata in research, it is important to reflect on how we could work towards alternative and radically inclusive ways of living and knowing together with biodata and multiple bodies [40].

3 Goals

This workshop will bring together a diverse community of researchers interested in engaging biodata in their research and design work. The discussion will allow us to draw connections and explore differences between how biosignals are treated, interpreted, and used across HCI subdomains and would allow us to build a shared vocabulary and understanding. We will map out the landscape of biosignal research and its application. For participants who are new to this field but interested in integrating biosignals in their work, this workshop would offer an introduction to this growing research space and valuable connections to form collaborations.

4 Workshop Structure

The workshop will begin with an introduction by the organizers and a short warm-up attunement activity. This attunement activity will help attendees to focus their attention and to reconnect with their bodies and their physiological signals, aligned with the topic of biosignals. Then, participants will engage in 3 rounds of small group work and discussion (4-6 participants per group). Each group will be joined by 1-2 organizers, who will focus on timekeeping and deliverables to ensure that the groups are ready to contribute to the large group discussion at the end. After each small group discussion, the moderator of that group will report to all other participants on the outcomes of the discussion.

Through discussion, we will aim to map out the **key challenges** and **opportunities** presented by biosensing technology. The 3 rounds of discussion will build towards this outcome: (a) T1: hands-on provocations (exercises) + discussion; (b) T2: roundtables based on participants' own research area; (c) T3: speculative design activity to illuminate ethical considerations. This way, the T1 exercise will introduce participants to working with biosignals and prompt them to reflect on relevant themes and challenges through hands-on first-person experience. T2 will connect these themes to participants' own work, building connections across disciplines. This will stimulate the cross-pollination of ideas between subdomains and encourage new connections to generate a wide map of observed challenges and opportunities. And T3 will prompt reflection on the overarching ethical consideration through an engaging speculative activity.

Introduction. We will set the goals and schedule of the workshop and do a quick round of introductions through an ice-breaking activity.

Warm-up Attunement Activity. Using principles of body-centric design, we will spend 10 minutes at the beginning of the workshop to practice an interoceptive activity to help participants *arrive* and re-focus for productive discussion. One of the organizers will lead a body scan exercise by directing participants' attention to their physiological activity, such as breathing and heartbeat.

T1 - Interpreting and Represenging Biosignals: Hands-on Provocations and Discussions. To stimulate reflection on opportunities and challenges emerging with the use of biosignals, we will invite participants to engage in a series of exercises set up in stations. Stations will include a basic biofeedback interface and playful prompt cards. The stations will be designed to prime participants for discussion by provoking questions and observations relevant

to using biosignals for analytics and as biofeedback. For example, one activity may include a visualization of all participants' heart rates in ranked order and a task to guess which heart rate belongs to whom and what it says about that person. This would prompt participants to think about their level of interoceptive awareness of their own physiology, how they make meaning from seeing their own and others' heart rates represented as a number, bar chart, emoticon, or abstract sound, and which effects seeing everyone's biosignals may have on a group dynamic.

T2 - Applications: Discussion Based on Participants areas of research. To connect the reflections to participants' own work, the second round of discussion will invite participants to imagine opportunities for integrating biosignals in their research. Rooting in the observations from T1, participants will discuss possible implications of the integration of biosensing across research domains, thus mapping out a landscape of application areas that connect their work. Participants will be encouraged to build connections and foster future collaborations by connecting common thematic threads.

T3 - Ethical considerations: Speculative design activity. We will lead participants through a speculative design activity to prompt the discussion about ethical considerations and principles emerging when integrating biosignals in multimedia interaction. They will be invited to imagine themselves as archaeologists of the distant future, discovering a yet-to-exist technology from 2040. They will then present a news report where they will discuss what this discovery taught them about the human society of that time. We will provide participants with prompt cards to stimulate their imagination of the future biosensing technology.

Summarizing Findings. A representative from each group will report on their key observations across all three activities. This way, we will present a map of common challenges, opportunities, and considerations, thus identifying future research directions for integrating biosignals in HCI. We will document these findings by note-taking and taking pictures of the whiteboards in the conference room. We will use these notes to write a blog post on Medium.com and report the observation in the ACM Interactions Magazine article.

Social Spaces. At the end of the workshop, we will encourage participants to go together for dinner or drinks after the workshop in a local restaurant to cultivate the community and network.

5 Anticipated Outcomes

The goal of this workshop is to bring together a community of researchers, designers, artists, and industry professionals working with biosignals to formulate a research agenda by exploring key challenges in the field, synthesize future research direction, and facilitate new connections and future collaborations between attendees. The discussions will be structured to create a map of common challenges observed across diverse domains of researchers and practitioners working with biosignals, and identify shared themes and strategies for addressing these challenges. This would foster a shared vocabulary across diverse domains and articulation of future directions for the field. We will report back to the community by publishing the summary of the discussion on the workshop website. We will report on key findings from the discussion in an ACM Interactions magazine and a Medium.com or conversation article. Together with interested participants, we will work on submitting a paper presenting an overview of the generated research agenda that will augment the existing systematic reviews of this research domain with an overview of practice-based reflections in this field. Attendees will be encouraged to work with the organizers and other attendees on future journal publications and co-organizing workshops and panels in academic and industry venues. Through this timely workshop topic, we will establish a lasting community focused on the design of interactive biofeedback systems.

6 Plan for recruitment of participants

We will recruit participants directly from prospective MUM attendees, as well as through relevant mailing lists and social media channels. The workshop is intended for a broad range of participants with diverse expertise in biosignals. We will target the recruitment of participants with established expertise with biosignals to share their practice-based insights. We will also invite early career researchers and those interested in the topic but new to the field of biosignals to bring in a fresh perspective and introduce them to this exciting domain.

Call For Participation. Biosensing technologies have become increasingly ubiquitous in Human-Computer Interaction. Biosignals provide novel opportunities for interaction, offering valuable insights into ordinarily hidden processes inside our bodies, revealing somatic information pertaining to our and other's bodies, emotions, health, and cognitive processes. However, the integration of biosignals in HCI presents many challenges pertaining to UX, I/O, interpretation of biodata, representation of biosignals, and broader ethical concerns. To map out the landscape of existing challenges and the future research directions, we invite participants working with or interested in biosignals to join a one-day workshop held at the 23rd International Conference on Mobile and Ubiquitous Multimedia (MUM'24) in Stockholm, Sweden. We welcome participants with a diverse range of expertise and backgrounds in HCI, design, digital art, psychology, education, health, philosophy, ethics, law, etc. Participants with established expertise in biosensing will have an opportunity to share their practice-based knowledge and foster new collaborations. Participants new to the field will have a hands-on introduction to the topic, helping them identify how and why they may employ biosensing in their work. See all details at http://physiohci.com/mum24ws/.

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References

[1] Miquel Alfaras, Vasiliki Tsaknaki, Pedro Sanches, Charles Windlin, Muhammad Umair, Corina Sas, and Kristina Höök. 2020. From Biodata to Somadata. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376684

[2] JR Bergstrom. 2014. *Eye tracking in user experience design*. Elsevier.

[3] Guillermo Bernal and Pattie Maes. 2017. Emotional Beasts: Visually Expressing Emotions through Avatars in VR. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 2395–2402. https://doi.org/10.1145/3027063.3053207

[4] Rafael A Calvo and Sidney D'Mello. 2010. Affect detection: An interdisciplinary review of models, methods, and their applications. *IEEE Transactions on affective computing* 1, 1 (2010), 18–37. https://doi.org/10.1109/T-AFFC.2010.1

[5] Jiaxun Cao, Hiba Laabadli, Chase H Mathis, Rebecca D Stern, and Pardis Emami-Naeini. 2024. "I Deleted It After the Overturn of Roe v. Wade": Understanding Women's Privacy Concerns Toward Period-Tracking Apps in the Post Roe v. Wade Era. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 813, 22 pages. https://doi.org/10.1145/3613904.3642042

[6] Sixian Chen, John Bowers, and Abigail Durrant. 2015. 'Ambient walk': a mobile application for mindful walking with sonification of biophysical data. In *Proceedings of the 2015 British HCI Conference on - British HCI '15*. ACM Press, Lincoln, Lincolnshire, United Kingdom, 315–315. https://doi.org/10.1145/2783446.2783630

[7] Francesco Chiossi, Yassmine El Khaoudi, Changkun Ou, Ludwig Sidenmark, Abdelrahman Zaky, Tiare Feuchtner, and Sven Mayer. 2024. Evaluating Typing Performance in Different Mixed Reality Manifestations using Physiological Features. *Proc. ACM Hum.-Comput. Interact.* 8, ISS (December 2024), Article 542. https://doi.org/10.1145/3698142

[8] Francesco Chiossi and Sven Mayer. 2023. How Can Mixed Reality Benefit From Physiologically-Adaptive Systems? Challenges and Opportunities for Human Factors Applications. In *Workshop on the Future of Computational Approaches for Understanding and Adapting User Interfaces*. arXiv, Hamburg, Germany. https://doi.org/10.48550/arXiv.2303.17978

[9] Francesco Chiossi, Changkun Ou, Carolina Gerhardt, Felix Putze, and Sven Mayer. 2023. Designing and Evaluating an Adaptive Virtual Reality System using EEG Frequencies to Balance Internal and External Attention States. *arXiv preprint arXiv:2311.10447* (2023).

[10] Francesco Chiossi, Ekaterina R. Stepanova, Benjamin Tag, Monica Perusquia-Hernandez, Alexandra Kitson, Arindam Dey, Sven Mayer, and Abdallah El Ali. 2024. PhysioCHI: Towards Best Practices for Integrating Physiological Signals in HCI. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 485, 7 pages. https://doi.org/10.1145/3613905.3636286

[11] Francesco Chiossi, Yagiz Turgut, Robin Welsch, and Sven Mayer. 2023. Adapting Visual Complexity Based on Electrodermal Activity Improves Working Memory Performance in Virtual Reality. *Proc. ACM Hum.-Comput. Interact.* 7, MHCI, Article 196 (sep 2023), 26 pages. https://doi.org/10.1145/3604243

[12] Anders Drachen, Lennart E. Nacke, Georgios Yannakakis, and Anja Lee Pedersen. 2010. Correlation between heart rate, electrodermal activity and player experience in first-person shooter games. In *Proceedings of the 5th ACM SIGGRAPH Symposium on Video Games* (Los Angeles, California) *(Sandbox '10)*. Association for Computing Machinery, New York, NY, USA, 49–54. https://doi.org/10.1145/1836135.1836143

[13] Abdallah El Ali, Rayna Ney, Zeph MC van Barlow, and Pablo Cesar. 2023. Is That My Heartbeat? Measuring and Understanding Modality-Dependent Cardiac Interoception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* (2023), 11. Issue 11. https://doi.org/10.1109/TVCG.2023.3320228

[14] Linda Hirsch, Florian Müller, Francesco Chiossi, Theodor Benga, and Andreas Martin Butz. 2023. My Heart Will Go On: Implicitly Increasing Social Connectedness by Visualizing Asynchronous Players' Heartbeats in VR Games. *Proc. ACM Hum.-Comput. Interact.* 7, CHI PLAY, Article 411 (Oct. 2023), 26 pages. https://doi.org/10.1145/3611057

[15] Kristina Höök. 2018. *Designing with the Body: Somaesthetic Interaction Design*. MIT Press, Cambridge, MA.

[16] Noura Howell, John Chuang, Abigail De Kosnik, Greg Niemeyer, and Kimiko Ryokai. 2018. Emotional Biosensing: Exploring Critical Alternatives. *Proc. ACM Hum.-Comput. Interact.* 2, CSCW, Article 69 (nov 2018), 25 pages. https://doi.org/10.1145/3274338

[17] Noura Howell, Laura Devendorf, Rundong (Kevin) Tian, Tomás Vega Galvez, Nan-Wei Gong, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. Biosignals as Social Cues: Ambiguity and Emotional Interpretation in Social Displays of Skin Conductance. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 865–870. https://doi.org/10.1145/2901790.2901850

[18] Noura Howell, Laura Devendorf, Tomás Alfonso Vega Gálvez, Rundong Tian, and Kimiko Ryokai. 2018. Tensions of Data-Driven Reflection: A Case Study of Real-Time Emotional Biosensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174005

[19] Noura Howell, Greg Niemeyer, and Kimiko Ryokai. 2019. Life-Affirming Biosensing in Public: Sounding Heartbeats on a Red Bench. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3290605.3300910

[20] Alexandra Kitson, Steve DiPaola, and Bernhard E. Riecke. 2019. Lucid Loop: A Virtual Deep Learning Biofeedback System for Lucid Dreaming Practice. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3290607.3312952

[21] Nataliya Kosmyna, Caitlin Morris, Utkarsh Sarawgi, and Pattie Maes. 2019. AttentivU: A Biofeedback System for Real-time Monitoring and Improvement of Engagement. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–2. https://doi.org/10.1145/3290607.3311768

[22] Sueyoon Lee, Abdallah El Ali, Maarten Wijntjes, and Pablo Cesar. 2022. Understanding and Designing Avatar Biosignal Visualizations for Social Virtual Reality Entertainment. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 425, 15 pages. https://doi.org/10.1145/3491102.3517451

[23] Kristen A Lindquist, Joshua Conrad Jackson, Joseph Leshin, Ajay B Satpute, and Maria Gendron. 2022. The cultural evolution of emotion. *Nature Reviews Psychology* 1 (2022), 1–13. Issue 11. https://doi.org/10.1038/s44159-022-00105-4

[24] Fannie Liu, Chunjong Park, Yu Jiang Tham, Tsung-Yu Tsai, Laura Dabbish, Geoff Kaufman, and Andrés Monroy-Hernández. 2021. Significant Otter: Understanding the Role of Biosignals in Communication. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 334, 15 pages. https://doi.org/10.1145/3411764.3445200

[25] Ewa Lux, Marc TP Adam, Verena Dorner, Sina Helming, Michael T Knierim, and Christof Weinhardt. 2018. Live biofeedback as a user interface design element: A review of the literature. *Communications of the Association for Information Systems* 43, 1 (2018), 18. https://doi.org/10.17705/1CAIS.04318

[26] Nick Merrill, John Chuang, and Coye Cheshire. 2019. Sensing is Believing: What People Think Biosensors Can Reveal About Thoughts and Feelings. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 413–420. https://doi.org/10.1145/3322276.3322286

[27] Jelena Mladenović, Jérémy Frey, and Jessica R. Cauchard. 2018. Dišimo: Anchoring Our Breath. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3170427.3186517

[28] Clara Moge, Katherine Wang, and Youngjun Cho. 2022. Shared User Interfaces of Physiological Data: Systematic Review of Social Biofeedback Systems and Contexts in HCI. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 301, 16 pages. https://doi.org/10.1145/3491102.3517495

[29] Seonghyeon Nam, Hayoung Song, and Youngwon Kim. 2021. Research on Contactless Bio-Signal Measurement Technology for Improving Social Awareness of Individuals with Communication Challenges. *Applied Sciences* 11, 11 (2021), 5169. https://doi.org/10.3390/app11115169

[30] Victoria Peng. 2021. Wigglears: Wiggle Your Ears With Your Emotions. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 492, 5 pages. https://doi.org/10.1145/3411763.3451846

[31] Mirjana Prpa, Ekaterina R. Stepanova, Thecla Schiphorst, Bernhard E. Riecke, and Philippe Pasquier. 2020. Inhaling and Exhaling: How Technologies Can Perceptually Extend our Breath Awareness. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3313831.3376183

[32] Chao Ying Qin, Jun-Ho Choi, Marios Constantinides, Luca Maria Aiello, and Daniele Quercia. 2021. Having a Heart Time? A Wearable-based Biofeedback

System. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services* (Oldenburg, Germany) *(MobileHCI '20)*. Association for Computing Machinery, New York, NY, USA, Article 29, 4 pages. https://doi.org/10.1145/3406324.3410539

[33] Luis Quintero, Uno Fors, and Panagiotis Papapetrou. 2023. Personalized Feature Importance Ranking for Affect Recognition from Behavioral and Physiological Data. *IEEE Transactions on Games* (2023), 1–10. https://doi.org/10.1109/TG.2023.3263070

[34] Mikko Salminen, Simo Järvelä, Antti Ruonala, Ville Harjunen, Giulio Jacucci, Juho Hamari, and Niklas Ravaja. 2019. Evoking Physiological Synchrony and Empathy Using Social VR with Biofeedback. *IEEE Transactions on Affective Computing* 13, 2 (2019), 10. https://doi.org/10.1109/TAFFC.2019.2958657

[35] Elaine Sedenberg, Richmond Wong, and John Chuang. 2018. *A window into the soul: Biosensing in public.* Routledge, Milton Park, UK, 75–98.

[36] Lin Shu, Jinyan Xie, Mingyue Yang, Ziyi Li, Zhenqi Li, Dan Liao, Xiangmin Xu, and Xinyi Yang. 2018. A review of emotion recognition using physiological signals. *Sensors* 18, 7 (2018), 2074. https://doi.org/10.3390/s18072074

[37] Lin Shu, Yang Yu, Wenzhuo Chen, Haoqiang Hua, Qin Li, Jianxiu Jin, and Xiangmin Xu. 2020. Wearable emotion recognition using heart rate data from a smart bracelet. *Sensors* 20, 3 (2020), 718. https://doi.org/10.3390/s20030718

[38] Petr Slovák, Joris Janssen, and Geraldine Fitzpatrick. 2012. Understanding heart rate sharing: towards unpacking physiosocial space. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 859–868. https://doi.org/10.1145/2207676.2208526

[39] Ekaterina R. Stepanova, John Desnoyers-Stewart, Alexandra Kitson, Bernhard E. Riecke, Alissa N. Antle, Abdallah El Ali, Jeremy Frey, Vasiliki Tsaknaki, and Noura Howell. 2023. Designing with Biosignals: Challenges, Opportunities, and Future Directions for Integrating Physiological Signals in Human-Computer Interaction. In *Companion Publication of the 2023 ACM Designing Interactive Systems Conference (DIS '23 Companion)*. Association for Computing Machinery, New York, NY, USA, 101–103. https://doi.org/10.1145/3563703.3591454

[40] Vasiliki Tsaknaki, Pedro Sanches, Tom Jenkins, Noura Howell, Laurens Boer, and Afroditi Bitzouni. 2022. Fabulating Biodata Futures for Living and Knowing Together. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1878–1892. https://doi.org/10.1145/3532106.3533477

[41] Laia Turmo Vidal, Ana Tajadura-Jiménez, José Manuel Vega-Cebrián, Judith Ley-Flores, Joaquin R. Díaz-Durán, and Elena Márquez Segura. 2024. Body Transformation: An Experiential Quality of Sensory Feedback Wearables for Altering Body Perception. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Cork, Ireland) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 25, 19 pages. https://doi.org/10.1145/3623509.3633373

[42] Wouter Walmink, Danielle Wilde, and Florian 'Floyd' Mueller. 2014. Displaying heart rate data on a bicycle helmet to support social exertion experiences. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 97–104. https://doi.org/10.1145/2540930.2540970

[43] Valtteri Wikström, Mari Falcon, Silja Martikainen, Jana Pejoska, Eva Durall, Merja Bauters, and Katri Saarikivi. 2021. Heart Rate Sharing at the Workplace. *Multimodal Technologies and Interaction* 5, 10 (2021), 60.

[44] Bin Yu, Mathias Funk, Jun Hu, Qi Wang, and Loe Feijs. 2018. Biofeedback for everyday stress management: A systematic review. *Frontiers in ICT* 5 (2018), 23. https://doi.org/10.3389/fict.2018.00023