Physiological I/O

Pedro Lopes
University of Chicago
United States
pedrolopes@uchicago.edu

Lewis Chuang
LMU Munich, Germany
lewis.chuang@um.ifi.lmu.de

Pattie Maes
MIT Media Lab
United States
pattie@media.mit.edu

ABSTRACT

Interactive computing systems are able to receive, as inputs, activity generated by the user's physiology (e.g., skin conductance, heart rate, brain potentials, and so forth). Besides health-related applications, this type of physiological sensing enables systems to infer users' states (e.g., task engagement, anxiety, workload, and so forth). More recently, a number of techniques emerged that can also stimulate physiological activity (e.g., electrical muscle stimulation, galvanic vestibular stimulation, transcranial stimulation). These can serve as outputs of an interactive system to induce desired behavior in the user. Taken together, we envision systems that will close the loop between physiological input and output—interactive systems able to *read* and *influence* the user's body. To realize this, we propose a Special Interest Group on Physiological I/O that will consolidate successful practices and identify research challenges to address as a community.

CCS CONCEPTS

• **Human-centered computing → Interaction paradigms**; *Interaction techniques*; **Haptic devices**.

KEYWORDS

wearables, physiological sensing, affective computing, muscle I/O, neural interfaces

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1 INTRODUCTION

The last decade has witnessed tremendous advances in personal computing. Wearable devices have blurred the distinction of where physiological and computing mechanisms begin and end. To name a few, eyewear (e.g., Focal), textile (e.g., Jacquard), and jewelry (e.g., Oura) that have proximal and constant contact with our skin, have enabled computing systems that can sense and reconstruct our physiological activity. This has led many researchers in our community to a renewed interest in developing interactive systems that *adapt* accordingly to the *user's state*, which is inferred by means of wearable physiological sensing.

Even more recently, the HCI community has been developing systems that not only allow for wearable sensing (input) but also for wearable actuation (output). Some examples include electrical muscle stimulation (EMS) [18] or Galvanic Vestibular Stimulation (GVS) [16] just to a cite a few. This effectively paves the way for HCI researchers to close the loop between physiological input and output, creating an entirely new type of interactive system that directly reads and influences the user's body.

1.1 Physiological Input: Sensing

Physiological activity is measured using diverse mechanisms, such as optical or electrical recordings. Broadly speaking, optical recordings allow for eye-and body-movements, pupil dilations, body temperature, and even blood oxygenation in the brain to be measured. Electrical recordings rely on skin electrodes that can be strategically placed to measure electrodermal activity (EDA), eye-movements, heart activity (ECG), electromyography (EMG), and electroencephalography (EEG). Sensor miniaturization resulted in not only advanced in-lab setups but also commercial wearables that monitor and interpret **physiological inputs**—such as jogging bracelets, sleep trackers, heartbeat watches, etc.

1.2 Physiological Output: Stimulation

Recent advances demonstrate that it is possible to influence the user's behavior and even mental state using stimulation techniques that directly influence the user's physiology, such as electrical muscle stimulation (EMS/FES) [13, 18], vestibular stimulation [16], transcranial direct current stimulation (tDCS) [20], electrical trigeminal stimulation [3], olfactory stimulation [1, 2], and so forth. These techniques offer the potential for interactive systems to respond via **physiological outputs**. For instance, in the case of electrical muscle stimulation this has been used to assist users in manipulating everyday tools they are not familiar with [14]; this interactive device delivers medically-compliant electrical impulses that cause the user's muscles to involuntarily perform the action that the users, themselves, are not trained to perform. Likewise, neuroscientists have shown that non-invasive stimulation of the brain can, for instance, improve arithmetic abilities [4], enhance working memory [21] or support decision-making [5]. Nonetheless, these systems are still isolated instances due to a number of open challenges in this field, which we present next, that range from hardware, software to interaction design.

2 CHALLENGES IN PHYSIOLOGICAL I/O

2.1 Challenge #1: Closing the loop between Physiological Input & Output

Achieving miniaturization, robustness, and comfort of *both* sensors and actuators is an open challenge. Conquering this will enable a

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path forward to more precise sensing/actuation, use in everyday settings and long-term usage. Furthermore, many of the software and hardware issues related to physiological input pertain to physiological output as well. However, a holistic approach is necessary in order to ensure that the same software and hardware developments for physiological sensing, which is more mature as a field, can be effectively leveraged for the purposes of stimulation.

Lastly, while the loop has been effectively closed in a few modalities, such as simultaneously sensing and actuating muscles [15], this does not generalize to many other modalities, such as smell, taste, and many others.

2.2 Challenge #2: Lack of precision

In many physiological interfaces the vision is still unattained simply due to a lack of precision. While improving the precision of sensors seems to progress at a stable pace, the same cannot be said for actuation, i.e., most recent actuators still not exhibit the level of precision needed for assisting users in most real-world tasks. For instance, taking the recent example of electrical muscle stimulation (EMS): while it has been a promising way to miniaturize force-feedback for wearables [12], it is still subject to a number of limitations, especially a lack of precision [17] (e.g., no enough precision to actuate the user in dexterous movements), but also a lack of comfort (e.g., while EMS produces a desired sense of force-feedback, it also produces an undesired tingling sensation, that causes discomfort to users). We expect that many of the current physiological I/O technologies in HCI are subjected to similar challenges.

2.3 Challenge #3: Ethics, privacy, and data security challenges

Enabling access to users' physiological activity and the ability to influence it raises ethical challenges with regards to personal privacy, data security, and the right to influence user states [7, 19]. We plan to gather, with our SIG attendees, potential strategies to address these issues through consideration of the consequences that could arise from the implementation of computing systems with Physiological I/O capabilities. We believe an understanding and early exploration of these challenges is critical for the field to advance ethically.

2.4 Challenge #4: Physiological principles > isolated use-cases

We argue that for this field to steadily move forward, we need to make advancements not only in isolated use-cases but establish working principles. In the case of Physiological I/O, these working principles are rooted in human physiology, i.e., they are physiological principles. For instance, recent work has shown that understanding the neurological function of the human body can allow us to design effective illusions. One such example is creating a sense of temperature in virtual reality by chemical stimulation of the user's trigeminal nerve (a nerve lodged inside of the nose) [2]. Similarly, to advance the existing precision of electrical muscle stimulation so that these systems can actuate the user's body more accurately, one needs to investigate the neuronal principles of muscle activation and human anatomy [17].

2.5 Challenge #5: Calibration across individuals

One, well-known, major challenge in wearable sensing is calibration of the sensed data across different individuals. This challenge is exacerbated in the case of Physiological I/O systems because not only users tend to be unique in their physiological activity, they also tend to be unique with regards to stimulation. For instance, the response to an EMS stimulus is different across users. This is well-known and documented in the HCI works that pioneered EMS for interactive systems, such as: "(..) stimulation level differed between users and was clearly dependent on the muscle and fat level and thickness of the arm" [11] or "(...) levels according to individual variations" [18]. These differences will occur in numerous modalities (e.g., olfactory, touch, sense of balance, etc.) and need to be resolved so these interactive systems can be successfully deployed in the mainstream.

2.6 Challenge #6: Design Guidelines

Guidelines will be required to ensure compatibility between different aspects of Physiological I/Os. Without a doubt, the physical safety of users should always be prioritized, especially since Physiological I/Os will actuate physiological mechanisms. Some clear examples already exist, such as guidelines that ensure the safe measurement and application of electricity on the human body [10]. Other aspects remain less clear, such as the implications of Physiological I/Os for different contexts. In addition, we expect that established design guidelines (e.g., safety) will have to co-adapt with other considerations (e.g., form factor, modality, user and task requirements) as the technology matures and apply to more domains.

2.7 Challenge #7: Agency

Lastly, we believe that the key challenge and opportunity that lays ahead for Physiological I/O is the question of "who did that?", in other words: the question of agency. While most interactive systems we are used to (e.g., a smartwatch, a mobile phone, etc), offer a clear cut of agency, the answer to "who did this?" is blurred when the interactive system has the ability to manipulate the user's body–one such extreme case are interactive systems based on electrical muscle stimulation. These are able to stimulate the user's body involuntarily [11, 18]. This can be used with great benefits to the user even beyond their bodily limits, e.g., an EMS system can be used to let a user react faster than humanly possible. Using such a system one can take a picture of a fast-moving object faster than we would normally be able to [9]. Researchers also found out that the naive assumption about EMS systems, which is to actuate as soon as the sensing system says "go", causes users to perceive this acceleration as *breaking their sense of agency*, i.e., users perceived it as an external force. This loss of agency is a shortcoming of Physiological I/O that needs to be addressed by researchers. However, there are promising recent efforts from our community to tackle the case of agency. For instance, Kasahara et al. tackled the loss of agency in EMS by delaying the muscle stimulation signal so that it is closer to the user's own reaction time, yet in a way that still results in the user's reaction time being accelerated. Surprisingly, they found that this preserves user's sense of agency [9], i.e., despite the action being accelerated by means of EMS, users perceived it as done by "themselves". Furthermore, this acceleration has been shown not only while the users are wearing the EMS system but even after they have removed the electrodes [8].

Moreover, while the question of agency is a major challenge for Physiological I/O, we argue it is also a design opportunity. Recent research in psychology distinguishes levels of consciousness into a tripartite model - conscious, unconscious, and metaconscious [6]. While most interactive devices tend to focus on the conscious pathway, requiring explicit user attention and action, they leave two pathways that provide opportunities to create new interfaces that can alter emotion, cognition, and behavior without demands on attentional resources. These direct interfaces might allow us to connect to cognitive processes that are in our perception but outside our conscious control [6], opening up a design space beyond just the question of agency.

3 GOALS OF THE SPECIAL INTEREST GROUP

The goal of this SIG is five-fold: (1) gather researchers who are conducting research at the intersection of technology and physiological sensing; (2) discuss open-challenges; (3) promote this research to larger audiences; (4) conceive plans for future events; and, (5) open up to a more diverse set of participants beyond the authors of this proposal.

4 ORGANISERS

Pedro Lopes is an Assistant Professor in Computer Science at the University of Chicago. Pedro focuses on integrating computer interfaces with the human body—exploring the interface paradigm that supersedes wearable computing. Some of these new integrated-devices include: a device based on muscle stimulation that allows users to manipulate tools they never seen before or that accelerate their reaction time, or a device that leverages the nose to create an illusion of temperature. Pedro's work also captured the interest of media, such as New York Times or NewScientist, and was exhibited at Ars Electronica and the World Economic Forum. Website: https://lab.plopes.org

Lewis Chuang is a lecturer in Informatics at the LMU Munich and leads Cognitive Neuroergonomics at the Leibniz Institute for Working Environment & Human Factors. He applies neuroscience methods and theories to understand how humans process information whilst interacting with digital technologies and automation. His work covers domains from wearable computing, augmented/virtual reality, teleoperations, and vehicle handling. Lewis is an associate editor for Scientific Reports, the International Journal for Human-Computer Studies, and the Frontiers Journal for Neuroergonomics. Website: https://lewischuang.com

Pattie Maes is a Professor of Media Technology in MIT's Program in Media Arts and Sciences. She heads the Media Lab's Fluid Interfaces research group that aims to radically reinvent the human-machine experience. She is especially interested in cognitive enhancement, namely how immersive and wearable systems can serve to improve human memory, attention, learning, decision making, communication, and their wellbeing. Pattie has received numerous awards for her work. For example, TIME Digital selected her as one of the top 50 technological pioneers of the high tech world. Her 2009 TED talk on "the 6th sense device" is among the most-watched TED talks ever. Website: https://www.media.mit.edu/people/pattie/overview/

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REFERENCES

[1] J. Amores, J. Hernandez, A. Dementyev, X. Wang, and P. Maes. 2018. BioEssence: A Wearable Olfactory Display that Monitors Cardio-respiratory Information to Support Mental Wellbeing. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 5131–5134. https://doi.org/10.1109/EMBC.2018.8513221

[2] Jas Brooks, Steven Nagels, and Pedro Lopes. 2020. Trigeminal-Based Temperature Illusions. 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, 1–12. https://doi.org/10.1145/3313831.3376806

[3] Jas Brooks, Shan-Yuan Teng, Jingxuan Wen, Romain Nith, Jun Nishida, and Pedro Lopes. 2021. Stereo-Smell via Electrical Trigeminal Stimulation. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM.

[4] Tobias U Hauser, Stephanie Rotzer, Roland H Grabner, Susan Mérillat, and Lutz Jäncke. 2013. Enhancing performance in numerical magnitude processing and mental arithmetic using transcranial Direct Current Stimulation (tDCS). *Frontiers in human neuroscience* 7 (2013), 244.

[5] David Hecht, Vincent Walsh, and Michal Lavidor. 2010. Transcranial direct current stimulation facilitates decision making in a probabilistic guessing task. *Journal of Neuroscience* 30, 12 (2010), 4241–4245.

[6] Abhinandan Jain, Adam Haar Horowitz, Felix Schoeller, Sang-won Leigh, Pattie Maes, and Misha Sra. 2020. Designing Interactions Beyond Conscious Control: A New Model for Wearable Interfaces. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3, Article 108 (Sept. 2020), 23 pages. https://doi.org/10.1145/3411829

[7] Roi Cohen Kadosh, Neil Levy, Jacinta O'Shea, Nicholas Shea, and Julian Savulescu. 2012. The neuroethics of non-invasive brain stimulation. *Current Biology* 22, 4 (2012), R108–R111.

[8] Shunichi Kasahara, Takada Kazuma, Jun Nishida, Kazuhisa Shibata, Shinsuke Shimojo, and Pedro Lopes. 2021. Preserving Agency During Electrical Muscle Stimulation Training Speeds up Reaction Time Directly After Removing EMS. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*.

[9] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. 2019. Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–15.

[10] Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. 2018. Design guideline for developing safe systems that apply electricity to the human body. *ACM Transactions on Computer-Human Interaction (TOCHI)* 25, 3 (2018), 1–36.

[11] Ernst Kruijff, Dieter Schmalstieg, and Steffi Beckhaus. 2006. Using Neuromuscular Electrical Stimulation for Pseudo-Haptic Feedback. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* (Limassol, Cyprus) *(VRST '06)*. Association for Computing Machinery, New York, NY, USA, 316–319. https://doi.org/10.1145/1180495.1180558

[12] Pedro Lopes and Patrick Baudisch. 2013. *Muscle-Propelled Force Feedback: Bringing Force Feedback to Mobile Devices.* Association for Computing Machinery, New York, NY, USA, 2577–2580. https://doi.org/10.1145/2470654.2481355

[13] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 939–948. https://doi.org/10.1145/2702123.2702461

[14] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2515–2524. https://doi.org/10.1145/2702123.2702128

[15] Jun Nishida and Kenji Suzuki. 2017. bioSync: A Paired Wearable Device for Blending Kinesthetic Experience. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3316–3327. https://doi.org/10.1145/3025453.3025829

[16] Misha Sra, Xuhai Xu, and Pattie Maes. 2017. GalVR: A Novel Collaboration Interface Using GVS. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (Gothenburg, Sweden) *(VRST '17)*. Association

for Computing Machinery, New York, NY, USA, Article 61, 2 pages. https://doi.org/10.1145/3139131.3141219

[17] Takahashi, Jas Akifumi, Brooks, Hiroyuki Kajimoto, and Pedro Lopes. 2021. Increasing Dexterity in Electrical Muscle Stimulation by means of Back of the Hand Actuation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*.

[18] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 543–552. https://doi.org/10.1145/1978942.1979018

[19] Rutger J Vlek, David Steines, Dyana Szibbo, Andrea Kübler, Mary-Jane Schneider, Pim Haselager, and Femke Nijboer. 2012. Ethical issues in brain–computer interface research, development, and dissemination. *Journal of neurologic physical therapy* 36, 2 (2012), 94–99.

[20] Filip Škola and Fotis Liarokapis. 2019. Examining and Enhancing the Illusory Touch Perception in Virtual Reality Using Non-Invasive Brain Stimulation. 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, 1–12. https://doi.org/10.1145/3290605.3300477

[21] Tino Zaehle, Pascale Sandmann, Jeremy D Thorne, Lutz Jäncke, and Christoph S Herrmann. 2011. Transcranial direct current stimulation of the prefrontal cortex modulates working memory performance: combined behavioural and electrophysiological evidence. *BMC neuroscience* 12, 1 (2011), 2.