Autonomic Interfaces for Augmenting Autonomic Processes

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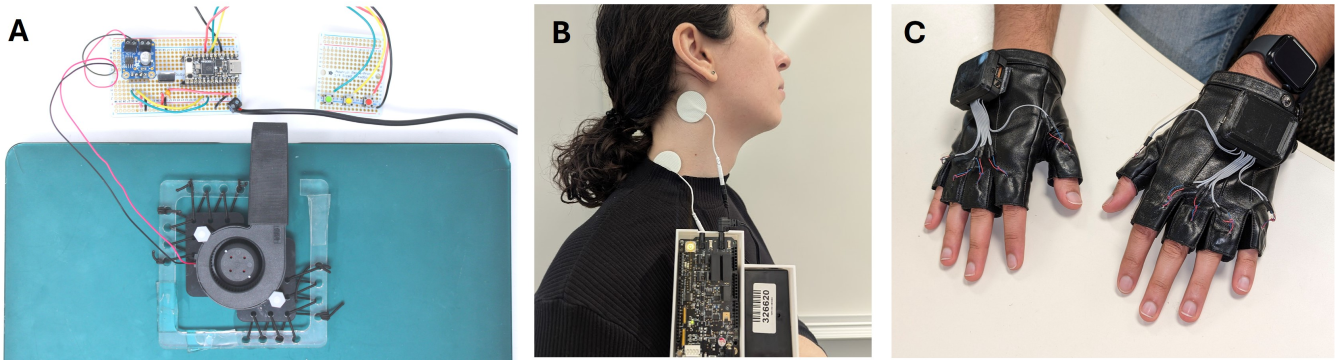

Figure 1: We introduce autonomic interfaces, devices that augment physiological systems while performing most of their functions implicitly, and discuss their user experience through three examples: (A) BreathePulse, a airflow-based breathing guide. (B) Vagus nerve stimulation to modulate satiety. (C) Passive haptic learning gloves for implicit motor learning.

Abstract

Autonomic processes are responsible for maintaining the most vital bodily functions, yet physiological interfaces have had limited success in continuously augmenting these functions. A new wave of wearable and ubiquitous devices have begun to sense and actuate autonomic processes of the human body while requiring little deliberate input from the user. In this position paper, we explore three examples of such devices from our work: An airflow breathing guide, a nerve stimulator for modulating satiety and a haptic glove for implicitly learning piano. The design and experience of these devices provide a unique perspective on control and awareness in interaction. We synthesize common trends for the design of "autonomic interfaces," sensorimotor devices that augment users' abilities implicitly by mirroring the mechanisms of autonomic physiological processes.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; *Interaction techniques.*

Keywords

sensorimotor interaction, wearable, haptic, autonomic computing

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1 Introduction

The most critical processes of the body are unconscious. Autonomic processes, such as the control of the heart, sweating, and hormone release, are essential for maintaining homeostasis and ensuring that the body functions properly. The autonomic nervous system (ANS) that regulates these processes enables us to adapt to different environments, and has a powerful influence on our behavior [4]. However, recent systems that aim to augment users' abilities have primarily focused on perception and motor control [15]. In contrast, autonomic processes have been treated as mechanisms that should be trained rather than augmented.

Existing HCI approaches rely on teaching users skills for physiological regulation, under the assumption that these will be used voluntarily in daily life. A broad range of gamified and task-based biofeedback approaches have been proposed to provide voluntary control over physiological processes [16]. These systems influence various processes including breathing [12], stress regulation [13], and affect [22]. Yet, the attention demands of these systems make them unsustainable for continuous use, and practical usage of learned skills appears limited. Likewise, personal informatics and just-in-time intervention approaches have relied on users to voluntarily act on feedback. These systems are highly dependent on sustained motivation, attention, and time, making them have limited effectiveness [1]. Considering these limitations, we reflect on approaches to managing autonomic processes beyond HCI.

The oldest and most traditional approach to modulating autonomic processes is medication, such as melatonin or caffeine [9]. While convenient, medication is dependent on chemical metabolization, so effects often spike after intake and decay over time. Thus, medication is unsuitable for systems where timing is important.

Numerous biomedical devices have emerged to fill this gap. A pacemaker senses electrical activity in the heart and moderates heart rhythm with electrical pulses. An artificial pancreas – a system combining a glucose monitor with an insulin pump – continuously adjusts insulin levels to manage blood glucose levels. A common trend in such devices is that they support dysfunctional autonomic processes by replicating the function of the original organ.

The approach used in these organ-level biomedical devices for modulating autonomic function serves as inspiration for how wearable systems can augment physiological processes without depending on users' deliberate actions. We propose that to *continuously* and *effectively* augment autonomic physiological processes, devices should mirror the function of the process that they are interfacing with. For example, when supporting breathing, systems should mimic the *action* of breathing, as used by aSpire [2] and BreathePulse [6], rather than merely the pattern.

We consider computing devices that augment physiological systems while performing most of their functions implicitly, without requiring conscious engagement or explicit control, to be **autonomic interfaces**. Note that we do not limit this definition to autonomic processes; just as autonomic processes may interface with a wide range of physiological systems, so too can autonomic interfaces. To exemplify the autonomic interface paradigm, we discuss three examples (shown in Figure 1) from our own work that each target different physiological processes: an airflow breathing guide, a nerve stimulator for modulating satiety, and a haptic glove for implicitly learning piano. Although these devices have distinctly different applications and form factors, they share several commonalities in their design and user experience.

2 Three Devices for Implicitly Modulating Physiological Activity

2.1 Guided Breathing with BreathePulse

BreathePulse is a ubiquitous, airflow-based peripheral breathing guide [6]. BreathePulse mirrors the rhythmic airflow of breathing. By turning a fan on and off repeatedly and guiding it through an air nozzle, BreathePulse generates a stream of subtle, pulsing airflow and directs it to the user's nostrils. The system is designed for encouraging slow and deep breathing while demanding minimal attention, and can be mounted on the back of a laptop. The rate of the pulsating airflow is personalized, set to 75% of the user's respiratory rate at rest, so that the target breathing rate is distinctly slower but achievable. As shown in Figure 2A, the respiratory rate is sensed using a Vernier GoDirect Respiration Belt, and streamed over Bluetooth to the laptop connected to BreathePulse.

In a lab study with 23 participants, we found that BreathePulse successfully encouraged slow breathing and promoted mindfulness, especially when participants were not simultaneously engaging in a cognitively intensive task. On the other hand, using the system increased workload and some users reported that they were actively paying attention to the device or their breathing. Such a result contradicted our goal of an implicitly controlled breathing guidance system, so we further investigated these results to better understand why only some users used the system implicitly.

Study participants perceived BreathePulse as a ambient device and a part of their environment. One participant described the system as similar to having a pet, indicating they conferred an independent agency to the system. In a questionnaire, half of participants said that they paid significant attention to the device, while the other half did not. Participants who paid attention to the device had a signifcantly lower respiratory rate, and sustained slow breathing for longer than those who did not; but they also reported higher workload and distraction, clearly showing the cost of explicitly controlling breathing. These participants were often concerned about the airflow being too weak to detect, and were less interested in using the system. Meanwhile, participants who did not pay attention to the device were more satisfied with BreathePulse, and found it more relaxing. Some of these participants were worried that they had "failed" in the guided breathing task, but quantitative results showed that their respiratory rate was still lower than the control condition, although not as strongly as participants who actively paid attention. These participants were particularly interested in the multisensory experience, such as using temperature and smell to augment the airflow and maintain relaxation. Overall, the divergence between participants' experiences shows that implicit control is valuable for improving coupling between ubiquitous devices and physiological systems. Given the mixed results between participants, we consider BreathePulse *marginally* implicit, as shown in Figure 3B.

The unexpectedly explicit interactions may have been due to the study design: Prompting users on how they should interact with the guided breathing system may have resulted in more attention being paid to the interface [2]. In addition, for movements such as breathing to be implicit, they must become habitual [20]. However, as the study only spanned an hour during a single session, habituation could not be evaluated. In conclusion, the introduction to a device, as well as the duration of interaction can play a significant role in integration with physiological processes.

2.2 Modulating Satiety with Vagus Nerve Stimulation

The vagus nerve plays a central role in the autonomic nervous system by connecting the brain to several organs including the heart, lungs, stomach and kidneys. Vagus nerve stimulation (VNS) has been used as a treatment for medical conditions such as anxiety, depression, and chronic pain [8]. Studies have also shown that VNS can modulate appetite and affect the rate of digestion [21]. We considered whether VNS could be used as a *momentary* intervention, in which people receive VNS immediately while eating. We hypothesized that using this approach to VNS could modulate satiety by gradually reducing appetite as participants continued eating, which could be useful for mitigating emotional eating behaviors.

We used transcutaneous cervical (neck-based) vagus nerve stimulation as a method to trigger the parasympethic response early while eating. Our application of VNS mirrors the parasympathetic rest-and-digest response upon eating until fullness by directly activating the same autonomic feedback system. Electrodes were placed on the neck of participants as shown in Figure 2B, which was used to transmit a weak (2-4mA depending on participant tolerance) electrical stimuli to the vagus nerve, just below the threshold at which participants described a tingling sensation. Electrical signals were generated by a NeuroStimDuino. After start of stimulation,

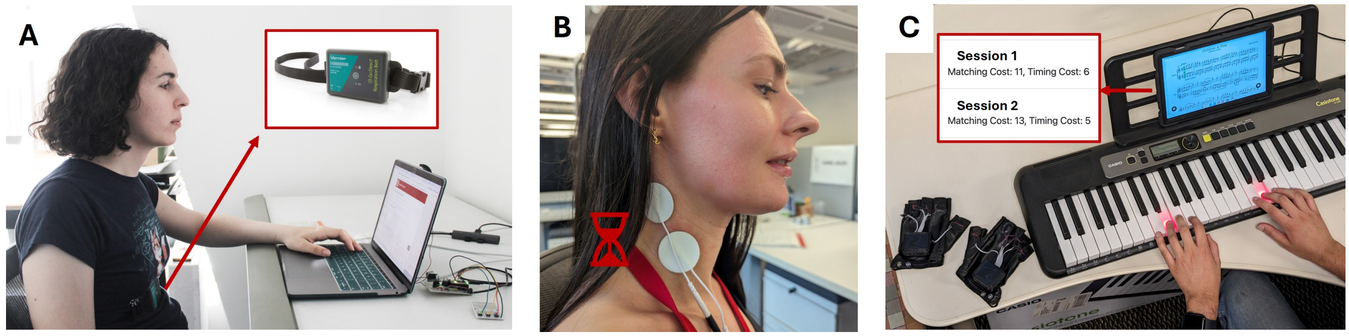

Figure 2: Usage and sensing approach for devices. (A) BreathePulse senses respiratory rate with a Vernier GoDirect Respiration Belt, and responds with airflow. (B) VNS gradually activates the parasympathetic response, achieving satiety over time. (C) PHL tracks piano performance through mistakes in practice sessions, and provides sequential vibration to reinforce learning.

participants were instructed to perform computer-based tasks while snacking. Participants were offered salty or sweet snacks based on preference, and were asked to stop and inform the researcher when they felt full.

As this study is ongoing work, we cannot comment on the effectiveness of the intervention, but have received interesting comments regarding user experience. Some participants described a cold sensation – likely due to the adhesive gel electrodes – and a mild tingling on their neck, but others reported no perceivable cues after the first few minutes. Participants did not engage with stimuli, indicating that the device successfully supported implicit control. Overall, participants tended to stop eating earlier, but also reported that they felt sleepier after receiving VNS. These results correlate with the typical signs of a parasympathetic response, but also point at some side effects of the intervention. Additionally, participants primarily discussed their state rather than interactions with the device, indicating that the stimulator successfully integrated with the regular mechanism of the vagus nerve, maintaining the agency of participants. Similar remarks have been made by patients with implanted nerve stimulators, some of whom have described the devices as "a part of them" and said that they had more agency than without the device [7]. In sum, devices can activate a physiological system to generate intrinsic cues, granting users agency over autonomic processes without needing them to pay attention to the physiological system or an interface.

2.3 Implicit Learning with Passive Haptic Learning Gloves

Passive haptic learning (PHL) is a technique for learning motor skills via repeated, implicit haptic training [19]. PHL uses ambient tactile cues as instructions to entrain sequential movements and associated information. Research on PHL has primarily explored its use as a standalone system for acquiring skills, starting with piano, without needing to actively practice them. In our work, we sought to combine PHL with active piano practice, in a mixed-agency approach that we call passive haptic rehearsal [5]. Moreover, for the first time, we evaluated the longitudinal impact of PHL on learning piano beyond the lab.

For two weeks, 20 participants were instructed to practice piano while playing two songs for one week each. During one of the weeks, participants combined 30-minute active practice sessions with two hours of passive rehearsal by wearing the PHL glove. Participants practiced piano at home, in the manner they preferred, supported by our web platform recording scores and giving performance feedback, and a Casio light-up keyboard. For each passive rehearsal session, the participants received a sequence of vibrotactile cues using one motor on each finger. We found that across proficiency levels, participants were able to learn 49.7% faster, reaching mastery two days earlier while using the PHL gloves.

While using the PHL gloves, some users remarked that initially the vibration felt too strong. As described by one user: "First couple of days I was getting used to it. In the middle it was like, okay, I'm just wearing these." As users got used to the device, they were able to comfortably use it in a range of tasks from running and typing to social events and lectures. However, users' biggest concern was the durability of the gloves, as the motor wires were exposed in the gloves designed for the study, which prevented users from doing tasks like playing with their pet or picking up objects. While users had to explicitly do tasks such as charging, turning on the device, and loading instructions from the web app, most of the system functioned implicitly through rhythmic vibrations when they were not engaging with the device.

The function of PHL mirrors central pattern generators in the brain and spinal cord. Central pattern generators are neural circuits that produce rhythmic motor signals, responsible for many repetitive rhythmic actions such as walking and breathing. Central pattern generators occupy an interesting physiological role, as they are autonomic processes that interact with several systems, despite not being a part of the autonomic nervous system [17]. PHL does not affect the autonomic nervous system – motor learning and tactile sensation are a part of the somatic nervous system. Yet, the mechanism of its action integrates with a deliberate process to automate it, which is why we consider the PHL gloves an autonomic interface, as shown in Figure 3B.

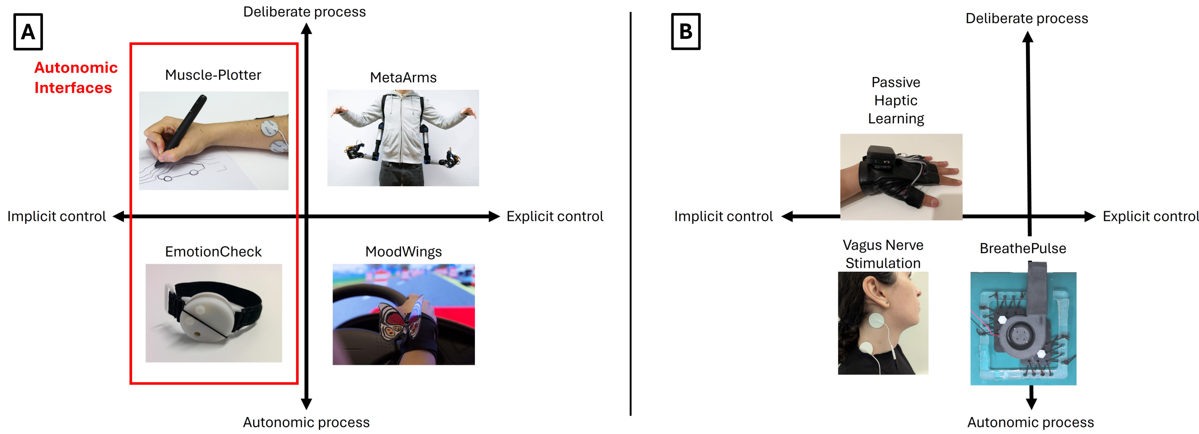

Figure 3: Autonomic interfaces augment both autonomic and deliberate physiological processes. (A) EmotionCheck [3] and Muscle-Plotter [11] are both autonomic interfaces as they implicitly sense and actuate physiological systems. Meanwhile, MoodWings [13] and MetaArms [18] are not autonomic interfaces as they require explicit control to function. (B) PHL [6] and VNS both provide implicit control over physiological processes, so they are both autonomic interfaces. BreathePulse [6] is only marginally autonomic as some users needed explicit control in our study.

3 Autonomic Interfaces

3.1 Common Trends

So far, we have introduced three systems for augmenting different physiological processes, and described how they each rely on implicit control and minimize attention demands. In this section, we consider patterns in the design and experience of these devices may be relevant to other interfaces.

Explicit control required to sustain an interaction can change over time, and different interactions with the same device involve different levels of control. All three systems we discussed showed the importance of a habituation period for the sensations provided by the device to normalize, and move to the periphery of attention. Moreover, BreathePulse users showed a clear divergence in behavior based on whether they paid attention to the device. Users of BreathePulse who explicitly controlled the device were distracted from other tasks they performed, and were less interested in using the device. Those who paid less attention cared more about the sensory experience and had a more favorable impression of the device. These comments also indicated that explicit control is not necessarily desirable.

Agency can be preserved even in the absence of explicit control. Users who tried the VNS device attributed the decision to stop eating to themselves, and did not consider the influence of the device. Even with perceivable cues, the effects of implicitly controlled devices can be challenging to attribute to the device versus the self. Some users of PHL gloves stated that they did not feel like they learned anything while using the gloves, but noticed that their scores had improved at the start of their next active practice session.

Not all interactions happen with user awareness. In both BreathePulse and PHL, users were not aware that they continued to interact with the device (via slower breathing and motor learning, respectively) when they stopped paying attention to it. Yet, the device continued to operate in the background. However, it's worth noting that both results indicate that interactions that occur outside of user awareness may have less effect than deliberate interactions. BreathePulse users who paid less attention to the device had a smaller decrease in their respiratory rate than those who did pay attention to the device. The effect of PHL on users' scores was smaller than a session of deliberate active practice despite the PHL session being four times longer in duration. On the other hand, its ability to mitigate forgetting between active practice sessions still made it worthwhile for the users.

Actuation can happen extrinsically, or intrinsically. Passive haptic rehearsal and BreathePulse both rely on tactile cues, which must pass through our senses to have an effect on physiology. Thus, they use extrinsic actuation. Instead, VNS directly stimulates nerves to activate the parasympathetic response, and any tactile sensations are unintended side effects. Therefore, VNS uses intrinsic actuation – it cues the body to generate a response which then affects other physiological systems. Intrinsic actuation is particularly conducive to autonomic interfaces, as they have limited perceivable sensation.

3.2 Next Steps

Next, we consider what is missing in these systems to facilitate deeper integration. Autonomic computing is a framework for making distributed systems sustainable, developed by IBM in 2001 [10]. Autonomic computing was similarly inspired by the autonomic nervous system, and aimed to confront the challenge of computer systems that grew beyond human capabilities to actively monitor, making it a valuable guide for designing autonomic interfaces as well. Autonomic computing has four key principles: self-configuration, self-optimization, self-healing, and self-protection. We present a modified version of these principles for autonomic interfaces.

Self-activation is the principle that devices should be able to activate and deactivate in the situations when they are needed. Self-activation is critical to deploying systems in the real-world, especially when they are intended as momentary interventions like

BreathePulse and VNS, and requires devices to sense the physiological system they aim to augment.

Self-adjustment is the principle that devices should be capable of adjusting their settings based on user activity and environment. For example, the constant breathing rate target was not optimal for users of BreathePulse, and personalizing patterns based on the task being performed by the user could be beneficial [14].

Self-maintenance is the principle that devices should be able to restore damage to the system, or give clear feedback during failure modes. This property is critical for long-term use, where many factors can damage components, as observed in our work on PHL.

Self-sustenance is the principle that devices should be able to provide energy for themselves. Some users of PHL remarked that the greatest difficulty of using the glove was charging it to full battery every night. Self-sustenance could be achieved through long-duration batteries, energy harvesting or convenient recharging.

4 Conclusion

In this paper, we introduced autonomic interfaces, a subset of sensorimotor devices focusing on implicitly augmenting physiological systems, and demonstrated it through three examples from our own work. All three devices presented are portable and functional, and we plan to bring all of them for physical demonstrations during the Sensorimotor Devices workshop. We look forward to engaging with the community on the potential of sensorimotor devices for augmenting autonomic processes.

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APPENDIX A Short Biography

Tan Gemicioglu is a PhD student in Information Science at Cornell Tech. Their research focuses on combining wearable health sensing and implicit interventions to unobtrusively maintain well-being. Their work has been published in top HCI venues such as ACM CHI and IMWUT.

Tanzeem Choudhury is a Professor in Computing and Information Sciences at Cornell Tech, where she holds the Roger and Joelle Burnell Chair in Integrated Health and Technology. She is a renowned expert in ubiquitous computing, mental health, applied machine learning, and digital health interventions. She has been elected as an ACM Fellow (2021) and inducted into the ACM SIGCHI Academy (2022).