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Review

Enhancing human emotions with interoceptive technologies

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Abstract

Historically, multiple theories have posited an active, causal role for perceived bodily states in the creation of human emotion. Recent evidence for embodied cognition, i.e. the role of the entire body in cognition, and support for models positing a key role of bodily homeostasis in the creation of consciousness, i.e. active inference, call for the test of causal rather than correlational links between changes in bodily state and changes in affective state. The controlled stimulation of body signals underlying human emotions and the constant feedback loop between actual and expected sensations during interoceptive processing allows for intervention on higher cognitive functioning. Somatosensory interfaces and emotion prosthesis modulating body perception and human emotions through interoceptive illusions offer new experimental and clinical tools for affective neuroscience. Here, we review challenges in the affective and interoceptive neurosciences, in the light of these novel technologies designed to open avenues for applied research and clinical intervention.

Keywords: Interoception; Interoceptive illusions; Cognitive augmentation; Aesthetic chills; Emotion prosthesis; Human-computer interfaces

1. Introduction

The process of interoception, whereby our nervous system integrates and unifies bodily information, has received extensive attention in recent years. Some fundamental questions concerning the mechanisms underlying the relation between emotion and interoception still remain unanswered. What is the exact role of interoception in emotion and cognition? Can we measure and intervene on the somatic markers leading to conscious cognition? Can we engineer human emotions through targeted somatosensory stimulation? Could such interventions be used as interoceptive training tools to improve mental health and somatic disorders? To address these issues, we introduce new technologies designed for the experimental study of the relationship between body perception and human emotions (e.g., [12,56,57,61,87]). Specifically, we discuss some recent results obtained with an emotion prosthesis designed to stimulate the sensory pathways underlying the sensation of chills (i.e., psychogenic shivers). These somatosensory interfaces

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aim to leverage the role of physiology in conscious cognition to produce synthetic emotions extending the scope of interoceptive awareness. In the words of Joseph Ledoux, "the opportunities for bodily feedback during emotional reactions to influence information processing by the brain and the way we consciously feel are enormous" [43]. Despite a growing interest in recent years [84,29,30,19,55,87], and a number of studies in human interoception revealing the role of physiology in higher-order cognitive processing [1,40,70,14,75], attempts at engineering bodily sensations and human emotions still lack a unifying theoretical framework. In this article, we first provide a brief overview of the key literature in affective neuroscience and discuss the interoceptive turn in brain science. We then review data concerning the crucial role of the body and peripheral nervous system in the emergence of conscious cognition. Finally, we outline opportunities offered by affective somatosensory interfaces for a radically new perspective on historical problems concerning human emotions. When coupled with contemporary theories in cognitive neuroscience, these interfaces allow novel functional applications in scientific, clinical and social settings.

2. Historical challenges in affective neuroscience

Affective neuroscience aims to elucidate the neural networks underlying emotional processes, and their consequences on physiology, cognition, and behavior [51,52,54]. Historically, the field has centered around the problems of defining universal human emotions and their somatic markers [18], clarifying the causal direction of emotional processes (from the brain to the body and conversely) and determining the role of the body and interoception in feelings and emotions [34]. These questions were first defined by the James-Lange theory [8], a counter-intuitive and influential physiological theory of emotions stipulating that physiology precedes and causes emotional processes (rather than the cognitive evaluation of exteroceptive signals). In short, feeling tears obstructing your visual field is posited to cause the feeling of sadness, and not the other way around. This theory has been the subject of a wide range of constructive criticism over the course of the 20th century and the role of body perception in conscious emotional processes is still debated to this day. However, support has grown for the notion of bidirectional influences on affect from both the body and brain, without a clear consensus on directionality [11].

One of the key questions in affective neuroscience still concerns defining basic human emotions and their *somatic markers* [16,17]. Several models and attempts at defining emotions and their core affects have been proposed. Within psychology, *the circumplex model of emotions* is still the most basic and widely accepted description of emotions [58]. This model distributes emotions in a two-dimensional space of arousal (i.e. quantity of emotion) and valence (i.e. quality of emotion) and can be linked to theories of approach and avoidance, whereby positively valenced pleasurable emotions trigger approach (e.g., joy), and negatively valenced aversive emotions causes one to withdraw from its surroundings (e.g., sadness). A recent application of the circumplex model of decision-making emotion in the context of cognitive dissonance was devised and tested in [22], suggesting that the structural two-dimensional model may be enough to explain a large part of the spectrum of human emotional experience. However, the circumplex model of emotions also has strict limitations and lacks predictive power as it fails to account (among others) for the dynamics and variety of somatic markers. More recent models describe emotions as evaluative homeostatic processes driving behavioral programs relevant to the needs of the organism [26,52]. In these models, basic emotions are dynamic subcortical networks evaluating sensory-motor information [63] as a function of homeostatic needs in a changing environment [53,52]. Their function is to allow sensory systems to overcome the constraints imposed by their limited processing capacity [85]. One of the key issues in the computational modelling of core basic emotions is the problem of *salience detection*. How does the brain know what to approach or what to avoid? How is saliency registered consciously through bodily changes and their conscious perception?

Recently, new questions emerged as the research on human emotions took *an interoceptive turn*, whereby a growing number of researchers in cognitive neuroscience took interest in the role of body perception in cognition [24]. This new interoceptive neuroscience aims to bring forth a better understanding of the conscious self, by bridging the gap between first-person subjective feelings and their third-person objective models [70]. In the line of these attempts to make sense of emotions in terms of interoceptive inferences, we introduce technology allowing researchers to address the problem of causality in emotional processes quantitatively by intervening on the underlying sensory pathways through controlled somatosensory stimulation (i.e., interoceptive illusions). The complex interplay of cognitive and physiological factors involved in emotional processes makes order and causality difficult to disentangle in affective neuroscience. Interoceptive illusions and experiments in misattribution of arousal offer an initial probe, wherein experimenters modulate a subject's physiology in order to alter psychology. Experiments have shown, for instance, that inducing increase heart rate via exercise facilitates romantic attraction to confederates [86]. This effect is attributed to a subject's misattribution, or misinterpretation, of increased heart rate as due to attraction as opposed to exercise. Other experiments have manipulated various forms of physiological emotional feedback [29], including facial muscles [78], to manipulate emotion (e.g., [42,20]). Yet many of these studies have failed to replicate, and as such the paradigms for influencing the body to influence the mind remain opaque [77]. Hence, new research tools allowing researchers to translate techniques into the wild, as well as test them in controlled laboratory settings, are necessary for addressing these issues in these applied affective neuroscience.

3. The interoceptive turn in emotion research

As mentioned, affective neuroscience has recently shifted its attention to the study of body perception, consolidating the research field of *interoception* [79]. Broadly speaking, interoception is the mechanism by which one becomes aware of its sensations, i.e. nervous system's processing of sensory signals (for a historical review of the notion see [9]). Indeed, the role of body perception in emotion has long been underlined by key theoreticians in psychophysiology (e.g., [4,39,60,7]). Interoception can be divided into multiple components such as proprioception (kinesthetic sensors for posture, position, and balance of the body), and somatoception (somesthetic sensors for maintaining internal homeostasis, dealing with internal changes of the body). Interoception is usually distinguished from exteroception (aesthetic sensors for vision, olfaction, touch dealing with aggregating changes in the external world). Exteroception is the perceptual synthesis of states of the world beyond the body, whereas interoception is concerned with internal body states.

Most interoception occurs *below the level of conscious awareness* and consists in making sense of large amounts of predominantly *noisy* sensory data [40]. However, conscious awareness and metacognitive reflection upon sensory signals exists, especially during adaptation to new or demanding situations (e.g., nausea during disgust, tachycardia during fear, chills during awe). These conscious processes, wherein we become aware of our bodily reactions to the environment, are critical to emotional processes [48]. Historically, identifying the causal directions in the relationship between interoception and emotion has been a great challenge. Some theories stipulate that emotional activity is an interpretation of bodily activity, valenced in terms of fight-flight readiness and approach-avoidance mechanisms (the Lange-James theory, or the somatic marker hypothesis), while others oppose this view and defend a top-down view whereby emotions drive action tendencies and behavioral programs (sometimes referred to as cognitive appraisal theory). At the anatomical level, studies have examined the neural bases of emotion and interoception [13,14]. A number of imaging and lesion studies, following on Damasio's somatic marker hypothesis and led in large part by Craig, indicated that the anterior insular cortex plays a key role in the integration of bodily states and subjective feelings. This region of cerebral cortex plays a critical role in many processes such as reward-driven decision-making, arousal, reactivity to emotional stimuli, and somatic processing. Interestingly, these regions also supports social cognition and empathy [75]. Despite a huge amount of empirical behavioral studies and neurophysiological data from lesion studies in neuropsychology highlighting the role of the insula and somatosensory cortex in emotion regulation, it remains difficult to elucidate the causal directionality of emotional processes through robust quantitative predictions.

Recently, a unified framework for interoceptive science has been proposed by leading researchers in the field [40]. This framework is largely influenced by the cognitive science of predictive coding [5,23], or active inference, whereby the mind and its peripheral body are described as a system of prediction and control aiming to minimize variational free energy (i.e., surprising states). In this context, interoceptive signals are predictions made by internally generated models, and sensations are hypotheses based on sensory evidence. Interoceptive perception is the synthesis that best explains, or most greatly reduces surprise with regards to, interoceptive sensations. These interoceptive representations – or inferences – are updated on the basis of ascending prediction errors, where descending predictions provide setpoints (target values for error-controlled regulation) for motor and autonomic reflexes [38]. In the context of emotions, this active inference view of interoception reconciles the dialectic between theories such as the somatic marker hypothesis (i.e., bodily sensations contribute crucially to emotion and action) and cognitive appraisal theory (i.e., emotion drives action) described above. In other words, active inference – when applied to interoception – implies that interoceptive perception and autonomic behavior are just two sides of the same coin. For example, perceptual synthesis may consider interoceptive signals as somatic markers of affect, while the descending predictions of these markers can drive action tendencies and elicit autonomic behaviors, i.e. emotions driving action in line with cognitive appraisal theory. In short, active inference ties the perceptual aspects of interoception to behavior, and provides an account of this filtered perception in the interoceptive domain.

This active inference perspective on interoception offers crucial new insights for psychiatry and clinical interventions (review in [50]). Affective and mood disorders, such as depression or generalized anxiety, are interdependent with changes in the body. Studies have also multiplied in recent years attempting to pin down the emotional role of cardiac [25,3] and visceral signals [14,2]. For example, Garfinkel and colleagues have shown that showing a fear stimulus in synchrony with the systole rhythmic phase of cardiovascular activity increases fear [32]. New concepts and metrics such as interoceptive attention, interoceptive awareness, interoceptive detection, interoceptive sensibility, and interoceptive accuracy [33,40] have emerged to disentangle conscious emotions and bodily states.

4. Interoceptive technologies for applied affective neuroscience

Surprisingly little research has been devoted to the topic of how technology may be used to enhance or generate emotion from stimulating somatic markers and modulating interoceptive inferences (i.e., somatosensory interfaces). In this section, we discuss its relevance for affective neuroscience in terms of interoceptive modulation, and present a case study for a novel kind of emotion prosthesis for the feeling of aesthetic chills (i.e., a device intervening on the somatic markers underlying the emotion in conjunction to its elicitation).

While somatosensory feedback has mainly been used for motor prosthesis [81,80,15], one of the oldest methods for mood modulation in psychiatry is direct brain stimulation through electrical means. In order to offer reliable alternatives to pharmacological medication over long time periods, bioelectronics and electroceuticals have emerged to modulate brain activity with small implantable electronic implants [74,46,83]. These can stimulate nerves and brain cells. Brain-implanted deep brain stimulation systems have had impressive success in improving mood disorders [37], and made communication possible for paralyzed patients [83]. To this day, the field of neurotechnology and neuromodulation has largely underplayed the active role of the body in the generation of conscious cognition and action, with the exception of direct transcutaneous stimulation of the vagus nerve, which has been used for treatment-resistant major depressive disorder [10], and can facilitate extinction of conditioned fear [55]. However, it is still a challenge to reliably modulate the human neural network with electrical stimulation, due to its complexity and severe adverse effects [46].

As an alternative to these treatments, we propose to leverage the role of physiology and body perception in emotion to produce reliable effects on cognitive functions and mental health. Here, we aim to emphasize a new line of research concerned with *interoceptive modulation*. Studies of interoceptive modulation have manipulated oxygen consumption [84], thermoregulation [30,41], acoustic feedback about heart-rate during an effort [82,29] and a list of other physiological influences on psychology (e.g., [12,56,57,87,36]). However, universal and quantifiable somatic markers for core emotions are still missing and we lack a good model of the expected effects of emotion prosthetics and somatosensory interfaces. To address the lack of reliable somatic markers for interoceptive modulation, our team developed a stimulation device to generate the emotion of aesthetic chills (i.e., psychogenic shivers), a dermal sensation of coldness associated with events of profound learning and fast generalization [27,35]. Chills are ordinarily a sensation associated with the thermoregulatory mechanism of shivers, a tremor of skeletal muscle dissipating heat to maintain core temperature stable. In humans, chills and associated phenomena such as goosebumps, occur in emotional contexts during a sudden resolution of uncertainty; i.e., an ‘aha’ moment associated to an abrupt drop in complexity [65,66]. Hence, usual elicitors for aesthetic chills are often complex stimuli such as music [59], narrative films [68], scientific insight [69], and social rituals [69,31].

In recent years, a wealth of studies have examined the emotion of aesthetic chills [6,64]. As a universal, quantitative and conscious somatic marker for a peak positive emotion, chills have crucial effects on a wide range of critical factors. They have been linked to pleasure and relaxation [66], learning, meaning-making, and curiosity [67,45] and have positive effects on altruism and prosocial behavior [31,61]. It is important to underline that chills occur either during positively-valenced and pleasurable events (positive chills as studied for example in [6]) or *ad contrario* during negative, threatening and aversive events (negative chills as studied for example by Zald & Pardo [88]). This has led to a theory of chills as a physiological marker of salience detection [62,67], allowing the brain to rapidly orientate in critical situations with relevance for survival [44] and high-level cognition [69]. More generally, chills have been described as a sudden acceleration of learning related to our vital need for information [64]. They may thus offer crucial insights into the aforementioned problem of salience detection through emotional pathways.

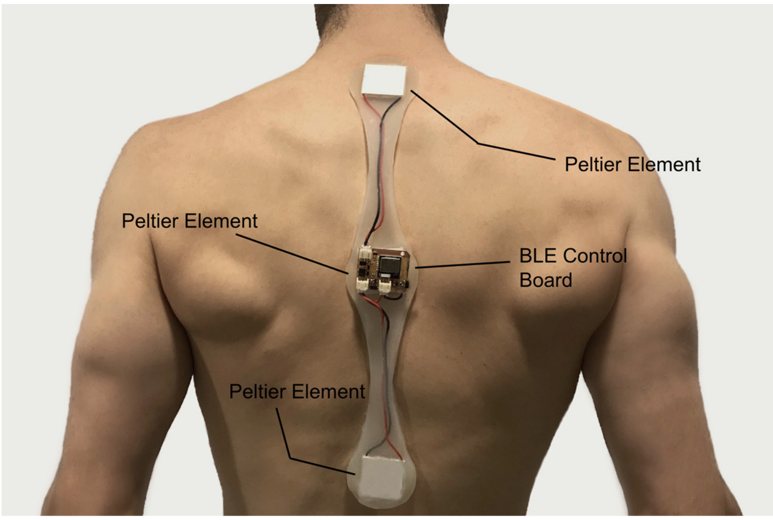

Fig. 1. The Frisson prosthesis: a device delivering thermal feedback in a manner closely resembling the internal chill, a traversing cold temperature from top to bottom.

Chills-related technology has been developed, but for measurement purposes only (review in [61]). Neidinger et al. [47] designed a wearable aiming to maximize chills through their social signalling. However, to our knowledge there has not been any attempt to trigger or enhance the emotion through somatosensory stimulation. As an interface for the emotion of chills, we built a prosthesis designed to artificially control and enhance the somatic basis of the emotion by intervening on the ascending sensory pathway (see Fig. 1). In essence, our protocol is similar to the facial feedback hypothesis and the seminal pencil studies demonstrating that holding a pen between one's teeth and activating the facial muscles of smiling increases the felt intensity of emotion, and its downstream effects [78]. The active inference interpretation of this effect is that the hypothesis "I am happy" is a plausible explanation for the proprioceptive signals generated by the act of smiling. Furthermore, if one commits to the inference that "I am happy", one will indeed predict this pattern of proprioceptive inputs, which will in turn be fulfilled through classical motor reflex arcs. Likewise, our prosthesis intends to modulate the interoceptive inferences at the basis of psychogenic shivers, wherein the hypothesis "I feel chills" becomes a plausible explanation for the interoceptive signals and their temporal organization.

Our prototype for delivering thermal feedback to imitate chills consists of three Peltier elements at different spatial locations down the spine: the nape of the neck, the middle of the back and the lower back. Additionally, a vibrotactile element sits on the nape of the neck alongside a BLE enabled control board. The device delivers thermal feedback in a manner closely resembling the internal chill, a traversing cold temperature from top to bottom of the spine. Preliminary studies (within-subjects design) evaluating the effects of the device on a small sample ($N = 21$) showed a significant increase in terms of both frequency and intensity of chills (Fig. 2). We found that participants wearing the device experienced chills at a greater frequency ($M = 4.00$; $STD = 2.90$) than participants without the device ($M = 2.76$; $SD = 2.86$). A pairwise t-test revealed that the device significantly increases the number of chills ($t = 3.2274$, $df = 20$, $p = 0.0021$). Participants also reported chills of a higher intensity of chills while wearing the device ($M = 5.62$; $SD = 2.44$) than without the device ($M = 4.33$, $SD = 2.57$), and a pairwise Wilcoxon test revealed significant difference in chills intensity across groups ($V = 104$, $p = .0327$). We also evaluated downstream cognitive effects typically associated with the emotion of chills, namely empathy and pleasure. We found that the device had significant effects in terms of empathy (degree of emotional contagion as reported by sharing speaker feelings) and pleasure (Fig. 3), but found no significant effect in terms of degree of shared speaker viewpoint (Table 1). Enhancing chills and managing to reproduce these downstream effects in a controlled way may prove critical for future experiments with clinical populations affected by, for example, attention deficit disorder, autism spectrum disorders or major depressive disorders [10]. Responses to synthetic chills may also provide reliable biomarkers for computational psychiatry, offering a unique opportunity to disentangle the relation between cognition and bodily signals during emotional processes, with both spatial and temporal precision [21,71–73,76].

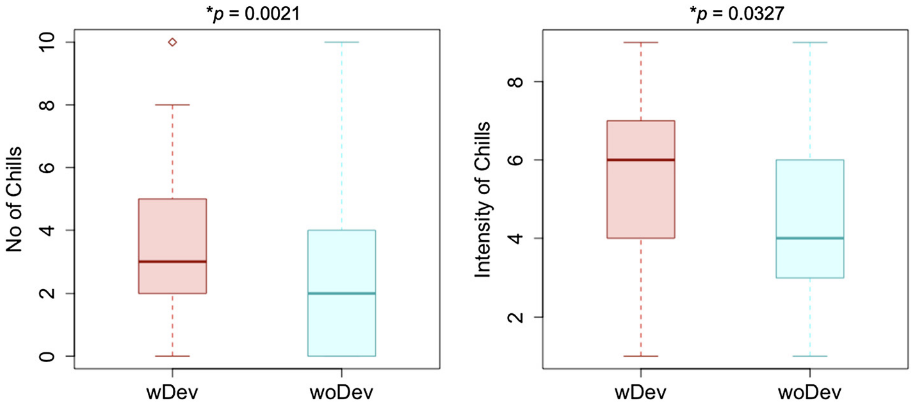

Fig. 2. Participants reported a significantly greater frequency and intensity of chills when wearing the device than without.

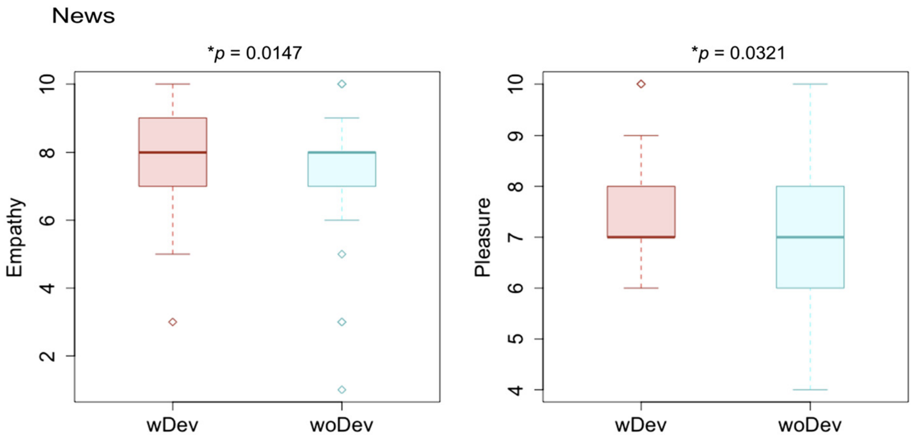

Fig. 3. Participants wearing the device reported experiencing significantly greater empathy for the speaker and pleasure during the experience with the device than without.

Table 1
Comparison of the intensity of chills, reports of shared feelings with speaker (i.e. empathy), reports of shared viewpoint with speaker, and perceived pleasure with and without the device.

Measure	With Device	Without Device	Pairwise Wilcoxon
Intensity of Chills	5.62 ± 2.44	4.33 ± 2.57	$V = 104$, $p^* = .0327$
Sharing Speaker Feelings	8.00 ± 1.73	7.19 ± 2.40	$V = 76$, $p^* = 0.015$
Sharing Speaker Viewpoint	8.33 ± 1.15	8.09 ± 1.79	$V = 18.5$, $p = 0.5$
Pleasure	7.66 ± 1.28	6.95 ± 1.66	$V = 38.5$, $p^* = 0.032$

5. Conclusion and prospects for future research

Somatosensory interfaces provide a novel method for affective neuromodulation by stimulating the body in a controlled way. How is this information integrated within interoceptive processing? What happens when you engage emotional pathways with controlled stimulation or amplify the sensory signals as a basis of interoceptive predictions? These questions and their answers can help refine the existing models of human emotion, interoception, and consciousness. They may provide new quantitative models for psychophysiology, theoretical neurobiology, and computational psychiatry. In terms of affective neuroscience, somatosensory interfaces offer a unique opportunity to study the mechanisms of salience detection and the consequences of conscious body perception on behavior and decision-making. Somatosensory interfaces such as our device open new pathways for clinical applications by augmenting or modulating interoceptive inferences and offer reliable non-invasive treatments for interoception-related mental disorders. Before application may be possible outside the laboratory, further testing is required, including a larger sample of a more diverse population, a thorough evaluation of the contribution of expectation effects to device functioning, and longitudinal assessments of habituation.

Dysfunctional interoception is increasingly recognized as a critical dimension for mental health, and the lack of proper technology to train interoception has been repeatedly emphasized [40]. Somatosensory interfaces can help identify *interoceptive biomarkers* and study their dynamics to improve the diagnosis and treatment of mental health disorders. For example, they may reduce anxiety sensitivity and correct prediction errors concerning the somatic markers of anxiety (e.g., dyspnea and palpitations) through biofeedback training [49]. Interoceptive awareness and accuracy have been found to predict resilience to stress and speed of recovery [28]. If deployed at scale and broadly disseminated, interoceptive training tools may offer critical insights for devising therapeutic tools for somatic symptom disorder patients (SSD). Some of the clinical populations most directly concerned by investigations into the modulation of interoceptive ability are panic disorders [49], autism spectrum disorder [25], and trauma disorders [28]. Studies in affective neuroscience should help identify the relevant neural pathways for targeted neuromodulation and novel methods can be devised to facilitate interoceptive learning and offer crucial insights to patients and clinicians.

Indeed, a number of questions remain open. Can we generalize the technique presented here to other universal emotions? Could we reproduce the findings concerning positive pleasurable chills to the case of negative aversive chills? In other words, can we generate artificial valence through interoceptive modulation? Are certain emotions more prone to control than others? Can we channel people's behavior for particular contexts (work, conflict resolution, education, etc.)? Can we drive learning, meaning-making and engineer knowledge qualia? Can we channel seriousness or fun, regulate mood, and build valence through physiology? What are the ethical prospects for somatosensory interfaces and how to deploy these tools in artistic, educational, and clinical settings? What will be the societal implications of shared physiology and intersubjective technologies? In recent years, the massive growth of connected devices and their miniaturization have led to unprecedented possibilities for experimental science. Technology has considerably extended our perceptual abilities (e.g., camera sensors), motor systems (e.g., cars and neuroprosthesis), long-term memory and cognition (e.g., computers). Somatosensory interfaces and emotion prosthesis offer a radically new perspective for affective neuroscience, and a unique opportunity to interface with and augment human introspective abilities.

Data availability statement

Supporting data is available at public repository: https://doi.org/10.7910/DVN/E4ZYOT.

Declaration of competing interest

The authors declare no competing interests.

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