**Observational Learning for Generative Holographic Therapy**

Samuel Solomon1, Yadong Xu1, Ruixiao Liu1, Jadelynn Dao1, José Lasalde Ramírez1, Jihong Min1, Dickson Yao1, Sarah Solomon2, Canran Wang1, Sijie Ji1, Wei Gao1\*

**Affiliations.**  
1Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA.

2Dartmouth Hitchcock Medical Center and Clinics, Adult Psychiatry Residency, Lebanon, NH, USA.

\*Corresponding author. Email: [weigao@caltech.edu](mailto:weigao@caltech.edu).

**Flow:**

1. **Despite being visually apparent that emotions come from physiology, there exist conflicting interpretations about how from unstandardized modeling approaches. The current successful ML methods (transformers) are not transferable to emotion modeling and datasets are not well formed, preventing any standardized and big-data approaches.**
2. **From a psychological perspective (foundational theory), anxiety is a compilation of emotions that start as physiological perturbations. These reflexes are not learned and exist across species, cultures, and life experiences. This can easily be visually decoded.**
3. **From a machine learning perspective, emotion modeling is difficult due to small multimodal input-output spaces with little to no overlap across datasets. Meta-learning can fix the issue of multi-modal input-output spaces and neural operators can help with generalize from a discrete to continuous domain. We should employ these techniques in a new foundational architecture that can handle differently sampled data similar to transformers, without losing the temporal information.**
4. **We propose Observational Learning as a new foundational architecture to overcome these challenges. OL architectures train an inverted model: generating an output causal signal that explains all observable inputs. The hypersampled profile can now accommodate different input sampling frequencies and missing data as it hallucinates each biomarker signal independently and only backpropagates on the observed timepoints. By decoupling each biomarker, OL models aims to justify each discretely sampled observable biological reaction, without needing the continuous signal, allowing it to adapt to different sampling frequencies.**
5. **Introduction to the datasets and therapy.**
6. **Summation**
7. **AGI emotional intelligence**
8. **Affine coupling layers and reversibility.**

**Abstract.**

**Summary paragraph.**

Advances in wearable technology have enabled the collection of various anxiety-based physiological datasets across multiple sensors and emotional questions; however, reliably associating these signals with emotional states remains an unsolved problem. This study presents a new neural architecture called Observational Learning for merging physiological datasets that enable researchers to work on fragmented out-of-domain datasets that currently cannot be meta-trained together. This work demonstrates the potential to share wearable data across platforms not only within mental health, but also other continuous health monitoring systems, enhancing the capabilities of wearable healthcare and offering insights into designing more robust, adaptive systems that respond to complex physiological patterns in real time.

**Main.**

Physiological responses are foundational to any emotional state, yet modeling affective experiences with time-dependent biometric patterns remains challenging when existing fragmented, sparsely sampled psychophysiological datasets have inconsistent biomarkers, emotion labels, and temporal resolutions, hindering attempts at universal, data-driven mental health interventions. However, without modern high-precision wearables, Darwin visually identified universal reflexes across the animal kingdom that are strongly linked to emotional sensations, suggesting that some affective and biological states are observably coupled1. Even with universally recognizable features, current anxiety monitoring systems frequently produce conflicting and poorly validated interpretations about stress-induced biomarkers2 in both academic (e.g., Ekman’s Facial Action Coding System3) and commercial (e.g., Apple Watch, Fitbit) applications. This contrasts large language models that reliably recognize emotions embedded within text using massive, curated datasets and robust transformer architectures4. Unfortunately, transformer methods are designed for semantic correlations, not temporal trends, making them ill-suited for learning wearable time-series patterns5. Attaining wearable artificial general emotional intelligence will therefore require new foundational architectures explicitly designed to handle fragmented time-dependent biomarkers that react to a broad spectrum of stressors and emotions6, as found in successful sentiment text-analysis frameworks7.

As early as Freud, psychophysiological models have studied momentary state anxiety (s-anxiety) through a compilation of emotional states8 that originate within physiological perturbations9. The specific emotions surveyed depend on the sample population’s ethnolinguistic background, where each coupled emotion acts as a weak classifier that allows the model to slowly converge to the affective profile. The smallest subset of these sentiments are labeled basic emotions, which are visually identifiable through universal facial expressions:3 observations that are not socially learned as even blind and deaf athletes experience emotional responses with predictable biological reactions10. In this regard, basic emotional reflexes likely reflect evolutionary adaptations that prime the body to confront potential threats, such as squinting in disgust to block harmful stimuli10. Spielberger measured variations of these feelings in the State-Trait Anxiety Inventory (STAI), a rigorously validated questionnaire with high internal consistency (α=0.86−0.96) that has been independently verified across cultures, age groups, professions, ethnicities, genders, and languages11–15; for the student population used in this study, the STAI-Y2 form has an internal consistency between 0.87 and 0.9115. Unfortunately, indirectly recording fundamental emotional features through bodily responses is less trivial than directly surveying a feeling. Currently, there are no psychophysiological models that generalize STAI scores across both experimental stressors (e.g. real-life activities, laboratory stressors) and labeling methodologies (e.g. different sets of complex emotions)6. This has allowed companies like Fitbit and Apple Watch to deviate from reporting clinically meaningful anxiety-metrics in favor of their own pseudo-anxiety scores16. The main research challenge therefore lies not in the conceptual link between physiology and anxiety, which is a superposition of basic emotional states, but in translating this link into reliable, data-driven models.

Academically accepted medical models address similar subjective experimental variance by generalizing across a diversly selected population, where regional sampling artifacts become harder to overfit, ultimately providing more actionable wellness insights17. One of the first large scale wellness models–the Framingham risk score–achieved this by merging small and noisy datasets collected by a range of researchers at different time periods17. Within machine learning, this is known as meta-learning a core set of sharable and adaptable transformations that are applied across different formulations of the same problem, essentially learning the problem space instead of the solving the issue directly18. This allows meta-learning models to accommodate heterogeneous input modalities with limited data, as found within different emotion datasets, thereby countering the data fragmentation problem that hindered previous approaches18. In parallel, neural operators—mathematical constructs that learn how discretely sampled signals transform within a continuous functional domain—have emerged as a prominent architecture for physics-informed neural networks that are suitable for solving differential equations found within scientific models19. For temporal signals in wearables, neural operators additionally overcome the constraints of localized, time-dependent observations by learning a continuous functional solution that can adapt to unseen datapoints20. By employing meta-learning strategies with neural operators, we begin forming a suitable framework for human emotion and activity recognition (HEAR) that addresses the previous bottlenecks by learning across new experimental modalities to focus on the optimal temporal patterns that relay clinically meaningful mental health information.

We introduce Observational Learning (OL) as a new foundational generative architecture that inverts conventional learning styles to co-train out-of-domain time-series signals using bidirectional meta-learned wavelet neural operators. As compared to standard machine learning approaches that learn across a collective set of input features, hindering their ability to accommodate failed readings, OL models learn by independently justifying how a generated hidden biological perturbation, termed the health profile (HP), can explain the granger-caused observable reactions. After training invertible orthonormal transformations, the HP represents a lossless embedded representation of each biometric signal whose transformations can be visually tracked by inverting each layer’s weights. OL models can accommodate different sampling intervals by explaining each discrete observation within a continuous functional domain, smoothing out the latent space to unseen or missing data and circumventing the need to realign features that introduce non-trivial artifacts. This approach mimics the scientific method when solving an inverse problem by retroactively learning a dynamic system through observing how signals propagate within. This new way of visualizing covariant shifts within deep neural architectures allows researchers to validate as well as tune different model instances with single-layer resolution. Observational learning allows researchers to generalize their pretrained models across dynamic real-life situations by providing an easy framework to link with a growing number of raw experimental biomarkers and stressors.

Unfortunately, within physiological datasets, there inherently exist motion artifacts and noise that can bias data interpretations, which is only exacerbated by the relatively small size of physio-emotion datasets compared to traditional large language models. To learn how to deal with these events, we employ meta-learning techniques to share weights and integrate multiple datasets together. Each path to the physiological profile can be broken up into 3 main sections: a signal-specific layer, shared meta-learning layer, and another signal-specific layer. Most of the model weights lie within the meta layer, removing the burden of small datasets, while the signal specific layers provide dataset-specific expressibility. Each signal-specific layer address subproblems within the broader task of physiological-emotion mapping, enabling few-shot learning on previously unseen datasets. Our core model has demonstrated strong performance after training on five physiological meta-datasets from the literature (WESAD, EMOGNITION, DAPPER, AMIGOS, and CASE) and has shown few-shot learning capabilities on two out-of-domain datasets that we compiled (EMPATCH). We aim to further enhance our model's generalizability and utility for the broader research community by establishing the first domain-agnostic physio-emotion model.

We validate our approach by metatraining four unique psychophysiological datasets concurrently, with few-shot training on two unseen models that uses common industry-grade as well as novel laboratory-fabricated platforms to ensure that OL models can generalize across both industry and academic pipelines. We further demonstrate real-time therapy through closed-loop visual, audio, and haptic feedback.

By understanding the complex relationship between physiology and emotions, we gain deeper insights into the intricacies of human emotional responses, creating opportunities for more personalized mental health interventions. Our approach was validated through generative visuals, sounds, thermogenic materials, and voice therapy sessions, all of which were personalized to the subject’s real-time emotion and biological profile. In early tests, we demonstrated the ability to modulate and reduce negative affective emotions and anxiety. We further validated our model’s predictions against the gold standard STAI- Y2 questionnaire as well as the Positive and Negative Affect Schedule (PANAS), showing strong alignment between our automated therapy outcomes and patient-reported results. This validation not only supports Ekman’s theoretical framework linking physiological and psychological domains but also establishes a new benchmark for closed-loop personalized therapeutic interventions, paving the way for automated, in-home, tailored mental health therapies.

\*\*\* Invertibility for inverse training, datasets, small Lipschitz constant

\*\*\* Therapy and materials and conclusion.

probing how the hidden state (p-profile) collectively justifies each observed signal (input feature).

predict each observable signal, By training the model from output (p-profile) to input (signal recordings), missing signal data, whether partial or full, do not invalidate other observations, since the model can justify each timepoint individually.

By training the model from output (the p-profile) to input (the measured signals), OL accommodates varying sampling frequencies and missing data, since the absence of one biomarker does not invalidate another. Each input is treated as an observable event explained by the hidden state, allowing the model to justify every discrete biological reaction individually. This decoupling of biomarkers from the core physiological representation reduces the need to discard samples due to motion artifacts or lost data packets. In doing so, OL fosters flexible, out-of-domain integration of time-series datasets,

Unfortunately, within, most datasets (e.g., WESAD, AMIGOS, CASE, Emognition, and DAPPER) have little to no overlap within biomarkers and emotion labels, complicating efforts to validate models against a universal standard (**SXX**).

Importantly, incorporating invertible and bijective formulations ensures that the transformations remain one-to-one and information-preserving, thereby enhancing reproducibility and interpretability. Together, these innovations establish a rigorous, flexible architecture poised to unify fragmented physiological datasets and deliver universally applicable, clinically meaningful insights into the emotional states that underpin human health and behavior.

To address the fragmented and sparse nature of current physiological emotion datasets, emerging scientific machine learning techniques such as meta-learning and neural operators offer powerful solutions. Meta-learning enables models to share a common set of core parameters, allowing rapid adaptation to new biomarkers and labeling schemes with minimal data, while neural operators map discrete, infinite-dimensional inputs to continuous functional spaces for smooth interpolation across out-of-domain conditions. By integrating invertible and bijective components, these neural operators ensure one-to-one, lossless correspondences that enhance reproducibility and reliability.

Further research into neural operators has

a core set of shared weights

By mapping discretely sampled, infinite-dimensional input-output spaces through continuous functional forms, neural operators (NOs) address these challenges by easily interpolating across unseen, out-of-domain examples. Integrating invertible networks within NOs further ensures a one-to-one lossless correspondence between input and output domains, providing a robust validation mechanism across different datasets and experimental conditions. Bijective neural operators (BNOs) further address the reproducibility issue within scientific modeling by limiting the number of solutions the model can converge to, ensuring consistent and reliable outcomes. By offering a rigorous and scientifically grounded approach, BNOs hold promise for solving many of the reproducibility problems in current scientific modeling for physiological datasets.

This is achieved through a series of reversible, learnable transformations that connect input and output states. By mapping all the biometric responses to the p-profile, OL models effectively learn a unified representation of a patient’s physiological state while maintaining the ability to add new biomarkers and timepoints as needed. Each observable event could therefore be considered a weak classifier of the p-profile, where more observations increase the prediction confidence.

When data is missing, which is a problem in any real-time wearable platform, the weak classifier cannot be used to reconstruct the physiological profile. Fortunately, once the model weights are trained and frozen, few-shot learning can be employed during inference to approximate the p-profile and provide a causal explanation (e.g., Granger causality) for each observation.

**Methods.**

Machine learning techbiques for multimodal things

This lack of biomarker and emotion validation promotes dataset-specific architectures that prevents data compilation and collaboration for an open-source generalizable physio-emotion model.

We present observational learning (OL) as a new foundational architecture for overcoming the current challenges with merging out-of-domain time-series datasets by decoupling biomarker and emotion weights, providing the model with a trainable path for different input signals and output emotions as seen within separate physio-emotion datasets currently in the literature. In OL models, each physiological feature (observable event) is treated as a response from a hidden biological perturbation, which we refer to as the physiological profile (p-profile). Observational learning therefore mimics the scientific method when solving an inverse problem (hidden state dynamics) by probing a system (p-profile, output state) and observing how the resulting perturbations (time series signals, input features) respond. Missing full or partial features do not invalidate other observations, allowing the model to backpropagate on incomplete datasets, minimizing the number of discarded samples. OL models can therefore learn the p-profile based on how well the hidden state can justify each observed vital sign collectively, using a core set of reversible learnable transformations between the output and input states. This allows us to condense all relevant physiological information within a common structure while maintaining the flexibility to add or remove new biomarkers and timepoints in the future. Once the p-profile has established a path to all observations, the network can be inverted to reconstruct the p-profile from any of these weak classifiers. Unfortunately, if samples are missing, as is common in real-time recordings, the model cannot affectively project the samples into the wavelet domain. Therefore, after the weights of the model are fixed, during inference, few-shot learning of the physiological profile can still explain (granger-cause) each observation.

The forward method cant be done.

By training the inverse model using a reversible map from the output latent manifold to a given input biomarker, OL architectures easily adapt to a new set of biomarkers as well as missing biomarker data, allowing researchers to meta-train on different real-world physiological datasets with a common set of shared weights.

Spielberger used this as a foundation for quantifying s-anxiety through the State-Trait Anxiety Inventory (STAI) questionnaire, which has undergone multiple independent assessments for validity and reliability across different cultures11–13, age groups, occupations, race, gender, and languages. Paul Ekman mapped these emotions to facial expressions within the Facial Action Coding System (FACS), proving that certain physiological responses are universally associated with emotions across cultures. Further analysis by

In 1895, Sigmund Freud realized that anxiety can be fully explained by discrete emotions, which according to the 1894 James-Lange theory meant that anxiety can be fully explained by physiology.

researchers have been unable to isolate single physiological signals that yield deterministic emotional states within a subject, partly due to the subjective interpretation of emotions and the complexity of physiological responses within the broader context of relatively small and noisy datasets.

WESAD dataset includes 15 subjects with wrist and chest recordings labeled with state anxiety scores, while the AMIGOS dataset involves 40 subjects with brain recordings labeled using the Big Five Inventory questionnaire. As relatively small and specific datasets, neither model has been used to generalize across other stress inducing activities nor validated against each other.

In contrast, mental health lacks comparable rigor, partly due to the subjective nature of emotions.

While physiological theories like Schachter-Singer’s two-factor model and Ekman’s Facial Action Coding System suggest measurable links between physical responses—such as heart rate or facial expressions—and emotions, attempts to identify deterministic biomarkers have failed due to the fragmented, noisy, and sparsely sampled nature of datasets.

In parallel, Schachter and Singer found that emotions are causal to physiological reactions, with the mind interpreting the body’s reaction as a ‘feeling,’ fundamentally link anxiety and physiological responses.

The continuous monitoring of mental health through wearable devices poses a unique and pressing challenge as compared to tracking physical well-being. While there is extensive literature documenting biomarker implications for physical illnesses, such as the Framingham Risk Score17, Susceptible-Infectious-Recovered model21, and the progression of diseases like Covid-19, mental health lacks clear, unbiased, and reproducible models. This knowledge gap becomes critical when addressing long-term anxiety, as acting on poorly understood models may exacerbate mental deterioration and lead to more severe conditions such as depression.

Without any standardized approach, physiological-based emotion modeling has been widely accepted within the psychological community

Anxiety modeling has been a longstanding endeavor in psychology. In 1895, Sigmund Freud defined anxiety as arising from emotional states, linking sensations such as tension, nervousness, and apprehension5. In 1966, Cattell distinguished anxiety that arise from emotional states and personality traits6. Building upon these definitions, Spielberger introduced the State-Trait Anxiety Inventory (STAI) in 1983 (Fig. 1), a well-investigated questionnaire that has undergone multiple independent assessments for validity and reliability across different cultures7–9, age groups9, occupations, races8, gender9, and languages. The STAI exam numerically quantifies both short-term, emotionally based state anxiety (S-anxiety) and long-term, personality-based trait anxiety (T-anxiety)10. Despite its population-based correlation to S-anxiety, the STAI survey relies on subjective user ratings of emotions, introducing biases to individual scores.

We validated the generalizability of the to new datasets via commercial and novel electronic skin wearable devices.

to decode well-observed physiological patterns within humans

The p-profile represents a signal-agnostic manifold: a latent construct capable of explaining each biological reaction independently.

Here, we present the first bidirectional wavelet neural operator (BWNO) trained within a newly proposed observational learning (OL) framework designed to overcome the current limitations of wearable datasets to develop the first open-sourced physio-emotion model as well as real-time personalized anxiety therapy.

, suggesting that some affective and physiological states are intrinsically linked. Spiel,

The problem of developing a reliable universal affective computing pipeline is hindered by sparse, biomarker-specific, and unevenly sampled wearable datasets, limiting the applicability of machine learning models that require large datasets and rely on domain-specific attributes.

By training the inverse problem, observational learning solves a key issue within wearable data analysis as the architecture does not require evenly sampled nor specific input features. This is achieved by projecting the PP manifold into the Fourier domain, solving the inverse problem, and mapping the oversampled solution back into the spatial domain at unevenly sampled time points. The key to convergence for OL models relies on the set of information being strongly correlated across different signal combinations, so that one can isolate a common domain with minimal signal-specific weights. For physiological data, prior literature has demonstrated this correlation through state-space models and multivariate regression, where heart rate data can be hallucinated through respiratory information. We use a 1:16 ratio for dataset-specific to shared weights, allowing for small datasets to be easily interfaced within our framework with minimal training. Within this framework, each biomarker serves as evidence – a weak classifier – for the underlying perturbation rather than as a mandatory input, where the model is trained from the hidden variable to the observed signals. We have demonstrated this through partially and fully masking out a given signal, while converging to a similar PP manifold to reconstruct the missing points.

The problems in compiling enough trainable data to associate physical and mental states prevent simple classification systems such as decision trees and fully connected networks from converging and generalizing across datasets. The main obstruction for using more complex predictors, is the lack of standardization across the literature for which physiological stimuli (sweat-metabolites, facial expressions, vital signs) as well as emotional responses (positive and negative affective states) should be recorded for a complete and universal physio-emotional dataset. Currently, there is no universal physiological model for emotion classification as many datasets compiled in the literature – WESAD, EMOGNITION, DAPPER, AMIGOS, and CASE – are signal-specific.

Compiling large datasets is hard and time consuming.

, each emotion model is only trained on a selective and highly specialized dataset, where it is impossible to generalize across publications. This problem is exacerbated by black-box machine learning techniques, which hinders how relevant any emotion study is to one another. Further issues include resampling features to match a neural architecture, random information loss during data transmission, sampling bias from emotion questionnaires, as well as data sparsity compared to the number of learnable parameters. Modern advancements in machine learning techniques including text-based sentiment analysis as well as neural operators offer a new way for overcoming these issues within the broader context of universal affective computing.

In this work, we present the first bidirectional wavelet neural operator (BWNO) trained through observational learning (OL).

Unlike fixed models, each new observation acts as a weak classifier, increasing the confidence that the manifold represents the body’s current state. We claim that missing or unaligned data points, which typically degrade model performance, have a limited impact on this flexible architecture.

One key innovation that allows observational learning the flexibility to generalize across input domains is bidirectional training. Through diffeomorphic transformations, OL models independently map the common ancestor to each observable output using a set of invertible weights, allowing for both inference and interpretation depending on the direction. During training, the model learns how to remove information from the manifold to validate each observation. While projecting different spaces into a common latent space is extremely difficult, by inverting the weights in observational learning during inference, the model can transform each individual signal into the manifold’s space. Each projection inherently contains noise that is smoothed out when considering all observations together. This approach mirrors scientific experiments, where multiple correlated observations are used to reconstruct the underlying properties of a system. Consequently, this architecture provides an interpretable framework for machine learning researchers, emphasizing not only the final predictions but also the mappings across each space, offering deeper insights into physiological events and their associated emotional responses.

**Discussion.**

Here we present our analysis from capturing real-time physiological signals in response to four unique experimental stressors, including music, cold pressure, exercise (biking), and virtual reality, to investigate the relationship between physiology and emotional responses. The custom-designed patch integrated four key sensors—electrooculography (EOG), electroencephalography (EEG), electrodermal activity (EDA), and temperature—enabling the continuous recording of both electrical and thermal signals (Fig 3a). These sensors provided rich, multidimensional data that form the foundation of the analysis.

**Device Design and Signal Processing**

Our device is composed of EOG, EEG, EDA, and temperature sensors that conformally adhere to the surface of the skin. Signals are collected and processed through a series of filters, amplifiers, voltage regulators, and a microcontroller unit (Fig 3bc). This robust design ensured that signals were processed in real-time and transmitted for further analysis.

Signal preprocessing, illustrated on the top right, involved filtering the raw physiological data to remove noise and artifacts while preserving essential features related to emotional states. The filtering and amplification stages were particularly important in handling high-frequency noise in EEG and EOG recordings, while EDA and temperature data required low-pass filtering to stabilize readings. These preprocessing steps ensured the data was clean and interpretable for the subsequent analyses of emotional responses.

**Real-Time Data Collection from Stressors**

The figure presents representative datasets from four different stressors—cold pressure, exercise, music, and virtual reality—demonstrating the robustness of the device in capturing physiological signals across various conditions. The datasets are displayed in the middle portion of the figure, showing the raw signal patterns for each stressor.

In the cold pressure and exercise experiments, we observed clear variations in physiological responses. For example, alpha power from the EEG readings, which are known to decrease during times of anxiety, distinctly dropped during the cold pressure test, indicating increased sympathetic nervous system activity. Similarly, temperature fluctuations were evident during the cold pressure experiment, correlating with participant discomfort. In contrast, music and virtual reality experiments yielded more moderate physiological changes, suggesting these stressors were less intense.

**Positive and Negative Affectivity Scores**

We also analyzed affective responses through positive and negative affectivity scores, focusing on how these scores varied across the cold pressure and exercise experiments. As shown in figure 3e, affectivity scores derived from physiological data showed distinct patterns. Cold pressure led to an overall increase in both positive and negative affectivity, while exercise was able to boost positive affectivity and decrease negative affectivity. The graphs show overlapping yet distinguishable distributions of affective states, with cold pressure eliciting a strong negative response and exercise producing mixed emotional states.

**Emotional Distributions and Correlations**

The violin plots (3g) represent the distribution of emotional states as measured by the State-Trait Anxiety Inventory (STAI). These distributions capture the range of emotional intensities experienced by participants, highlighting the variability across different stressors. Cold pressure induced a broader distribution of negative emotions compared to exercise, which showed a wider spread across both positive and negative affective states.

Lastly, the correlation analysis from the Positive and Negative Affect Schedule (PANAS) revealed significant relationships between emotional states (3h). The correlations confirm the model’s ability meta-learn a core set of transformations, while leaving only a small set of weights to differentiate each emotion.

**Implications for Personalized Interventions**

The data gathered from this study not only validate our device’s capacity to measure physiological responses but also demonstrate its potential in developing automated, personalized mental health interventions. By accurately mapping physiological signals to emotional profiles in real time, our approach could be used to tailor interventions such as music or virtual reality therapy to a patient's emotional state, offering a novel method for treating anxiety and mood disorders.

The results also set a strong foundation for future work, where further validation across larger and more diverse datasets will be critical. The combination of wearable sensors and machine learning can provide increasingly precise mappings between physiology and emotional states, ultimately leading to more robust, domain-agnostic models for therapeutic applications.

The intrinsic softness, thickness, and gas permeability of skin-interfaced electronics hold promise for long-term and continuous high-fidelity monitoring of physiological states. Recently, there has been many exciting progresses in the fabrication of ultrathin and soft wearables, as evidenced by elastomeric nanofiber mats1 and elastic conductor with microcracked structures2 and semiconductors3. While these devices exhibited seamless contact with skin, the fabrication typically involves electrospinning, iterative spin coating, and thermal evaporation, which are laborious and time-consuming. Moreover, the manufacture of large patches to cover the head or face presents challenges due to limitations in dimensions imposed by instruments such as spin-coaters and oxygen plasma cleaners. While the float assembly method shows promise4,5, achieving in-situ generation of microscale porosity remains fundamentally challenging.

Here, we present a phase-separated float assembly (PSFA) technique that achieves in situ phase separation of silver nanowires (AgNWs) from thermoplastic polyurethane (TPU) matrices at water-air interface. This process enables rapid (in minutes), facile and large-area (>200 cm2) fabrication of ultrathin elastic patches (~1 µm) and phase-separated porous elastic sensors (~6 µm). The resulting ultrathin porous electronic skin exhibits substantial improvement in unobtrusiveness, comfort, and intimate contact with skin. As illustrated in Fig. 2a, the fabrication begins with the preparation of a precursor solution containing polymer solution (TPU in tetrahydrofuran (THF)) and conductive filler solution (AgNWs in ethanol). Upon the injection of the nanocomposite solution into water bath, phase separation initiates due to the evaporation and dissolution of the volatile solvent (THF) and non-solvent (ethanol) into water bath, whereas water-immiscible TPU stays on water surface. This results in macroscopic Marangoni flow and microscale liquid-liquid demixing simultaneously (Fig. 2b). On the one hand, dissolution of THF and ethanol lowers the local surface tension, which results in a circular surface tension gradient near the droplet (Fig. 2b, (i)). This gradient induces Marangoni flow from the center to the boundary, which pushes the boundary expansion and mass flow of the precursor solution. This leads to a partially dried ultrathin nanocomposite film floating at the water-air interface. On the other hand, concurrent liquid-liquid demixing results in phase separation of the TPU-rich and TPU-poor phases (Fig. 2b, (ii)). Ag NWs with amphiphilic ligands (that is, polyvinyl pyrrolidone) reside in the PU-poor phase due to its immiscibility with TPU solution. This process generates co-continuous phases in three dimensions, completed by drying that creates continuous porous structures within the PU matrices.

The resulting porous nanocomposite consists of randomly distributed AgNWs confined within porous polymer matrices (Fig. 2c), forming conductive percolation networks that bridge interconnected pores across multiple scales. Unlike conventional spin-coating processes, the PSFA method enables the fabrication of large, thin, yet adhesive electronic skins suitable for multimodal stress therapy. These devices are stretchable, ultrasoft, and provide conformal contact with the skin for enhanced comfort and unobtrusiveness (Fig. 2d–f). Additionally, the porous conductor demonstrates exceptional durability and reliability, with only a slight resistance change (R/R₀ = 4.8) after 3,000 cycles of 25% stretching, compared to the non-porous control (R/R₀ > 200; Fig. 2h). The multiscale interconnected cellular structure further enhances porosity and breathability, facilitating skin perspiration (Fig. 2i) and improving long-term biocompatibility (Fig. 2j, k).

To evaluate the performance of our porous conductor for electrophysiological signal recording, we first examined the electrode-skin contact impedance. The ultrathin porous electrode showed notably reduced impedance compared to its thicker counterpart, primarily due to its intimate skin contact (Fig. 2l). Furthermore, electrooculogram (EOG) signals recorded before and after sweating using the porous on-skin sensors demonstrated quantitatively comparable patterns to those obtained with Ag/AgCl gel electrodes (Fig. 2m, n). Lastly, we present a comprehensive comparison of our Empatch with state-of-the-art materials fabricated by other methods, such as spin-coating and float assembly4, in terms of processing efficiency, large-area fabrication, breathability, wearability, sweat resistance, and electrical conductivity (Fig. 2o).

To accommodate dynamic skin deformations, we utilize strain-resilient interconnects composed of a porous liquid metal composite6, which enables reliable and robust sensing and therapeutic capabilities. This performance is demonstrated by the proper operation of a light-emitting diode array (Fig. 2p), which can be attributed to the stable electrical resistance of the interconnect under strain (Fig. 2q) and its resilience to various damage scenarios, including scalpel punctures, hammer impacts, and tweezer pricks (Fig. 2r). Furthermore, electrocardiogram signals recorded using the liquid metal composite wiring showed negligible variation before and after stretching (Fig. 2s).

**Methods.**

While rapid processing and reaction to physiological cues are a core function of the human body, the intricacies of how this occurs are not fully understood.

Modern approaches using machine learning and wearable devices are now exploring how everyday biomarkers contribute to one’s inner psychological state.

**Reference**

1. Darwin, C. *The Expression of the Emotions in Man and Animals*. (J. Murray, 1904).

2. Mohr, D. C., Zhang, M. & Schueller, S. M. Personal Sensing: Understanding Mental Health Using Ubiquitous Sensors and Machine Learning. *Annu. Rev. Clin. Psychol.* **13**, 23–47 (2017).

3. Constants across cultures in the face and emotion. *ResearchGate* https://www.researchgate.net/publication/17640481\_Constants\_across\_cultures\_in\_the\_face\_and\_emotion.

4. Demszky, D. *et al.* GoEmotions: A Dataset of Fine-Grained Emotions. in *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics* (eds. Jurafsky, D., Chai, J., Schluter, N. & Tetreault, J.) 4040–4054 (Association for Computational Linguistics, Online, 2020). doi:10.18653/v1/2020.acl-main.372.

5. Zeng, A., Chen, M., Zhang, L. & Xu, Q. Are Transformers Effective for Time Series Forecasting? Preprint at https://doi.org/10.48550/arXiv.2205.13504 (2022).

6. Vos, G., Trinh, K., Sarnyai, Z. & Rahimi Azghadi, M. Generalizable machine learning for stress monitoring from wearable devices: A systematic literature review. *Int. J. Med. Inf.* **173**, 105026 (2023).

7. Devlin, J., Chang, M.-W., Lee, K. & Toutanova, K. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. in *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)* (eds. Burstein, J., Doran, C. & Solorio, T.) 4171–4186 (Association for Computational Linguistics, Minneapolis, Minnesota, 2019). doi:10.18653/v1/N19-1423.

8. Freud, S. *Inhibitions, Symptoms, and Anxiety*. (Norton, New York, 1989).

9. Cognitive, Social, and Physiological Determinants of Emotional State. In: Psychological Review 69(5): 379-399. *ResearchGate* https://www.researchgate.net/publication/9090242\_Cognitive\_Social\_and\_Physiological\_Determinants\_of\_Emotional\_State\_In\_Psychological\_Review\_695\_379-399.

10. Matsumoto, D. & Willingham, B. Spontaneous facial expressions of emotion of congenitally and noncongenitally blind individuals. *J. Pers. Soc. Psychol.* **96**, 1–10 (2009).

11. Stojanović, N. *et al.* Reliability and validity of the Spielberger’s State-Trait Anxiety Inventory (STAI) in Serbian university student and psychiatric non-psychotic outpatient populations. *Acta Fac. Medicae Naissensis* **37**, 149–159 (2020).

12. Gustafson, L. W. *et al.* Validity and reliability of State-Trait Anxiety Inventory in Danish women aged 45 years and older with abnormal cervical screening results. *BMC Med. Res. Methodol.* **20**, 89 (2020).

13. Vitasari, P., Wahab, M. N. A., Herawan, T., Othman, A. & Sinnadurai, S. K. Re-test of State Trait Anxiety Inventory (STAI) among Engineering Students in Malaysia: Reliability and Validity tests. *Procedia - Soc. Behav. Sci.* **15**, 3843–3848 (2011).

14. Thomas, C. L. & Cassady, J. C. Validation of the State Version of the State-Trait Anxiety Inventory in a University Sample. *SAGE Open*.

15. Manual for the State-Trait Anxiety Inventory (Form Y1 – Y2). *ResearchGate* https://www.researchgate.net/publication/235361542\_Manual\_for\_the\_State-Trait\_Anxiety\_Inventory\_Form\_Y1\_-\_Y2.

16. Gagnon, J. *et al.* Comparing a Fitbit Wearable to an Electrocardiogram Gold Standard as a Measure of Heart Rate Under Psychological Stress: A Validation Study. *JMIR Form. Res.* **6**, e37885 (2022).

17. Wilson, P. W. F. *et al.* Prediction of Coronary Heart Disease Using Risk Factor Categories. *Circulation* **97**, 1837–1847 (1998).

18. Finn, C., Abbeel, P. & Levine, S. Model-Agnostic Meta-Learning for Fast Adaptation of Deep Networks. Preprint at https://doi.org/10.48550/arXiv.1703.03400 (2017).

19. Li, Z. *et al.* Fourier Neural Operator for Parametric Partial Differential Equations. Preprint at https://doi.org/10.48550/arXiv.2010.08895 (2021).

20. Lu, L., Jin, P., Pang, G., Zhang, Z. & Karniadakis, G. E. Learning nonlinear operators via DeepONet based on the universal approximation theorem of operators. *Nat. Mach. Intell.* **3**, 218–229 (2021).

21. Vallée, A., Faranda, D. & Arutkin, M. COVID-19 epidemic peaks distribution in the United-States of America, from epidemiological modeling to public health policies. *Sci. Rep.* **13**, 4996 (2023).