Physio-Stacks: Supporting Communication with Ourselves and Others via Tangible, Modular Physiological Devices

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Figure 1: We present simple modular bricks that support the easy creation and interfacing with physiological applications.

ABSTRACT

Our physiological activity reflects our inner workings. However, we are not always aware of it in full detail. Physiological devices allow us to monitor and create adaptive systems and support introspection. Given that these devices have access to sensitive data, it is vital that users have a clear understanding of the internal mechanisms (extrospection), yet the underlying processes are hard to understand and control, resulting in a loss of agency. In this work, we focus on bringing the agency back to the user, by using design guidelines based on principles of honest communication and driven by positive activities. To this end, we conceived a tangible, modular approach for the construction of physiological interfaces that can be used as a prototyping toolkit by designers and researchers, or as didactic tools by educators and pupils. We show the potential of such an approach with a set of examples, supporting introspection, dialog, music creation, and play.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools.**

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Physiological Computing, Positive Computing, Tangible User Interfaces, Modular Programming, Essay/Argument

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1 INTRODUCTION

We live in a world where technology is steadily becoming more capable of monitoring and reacting to our actions and internal state. This takes many forms, from phone activity tracking, to dedicated physiological devices such as smart-watches. The aggregation of this data allows us to know more about ourselves and make intentional, positive changes in our behaviour, for example to better exercise. This is the main driving force behind the *Quantified Self* movement [82]. Beyond the individual, physiology both informs us about others' physical and emotional states, and reacts to our social interactions [33]. This is reflected in the social component of self-monitoring, where information about others can be accessed and compared against.

Yet, the popularity of self-monitoring technology is not without caveats, as the aggregation of data carries two different kinds of obscurity: *meaning* and *process*. First, *Quantification leads to objectification*: data visualization and numerical representations can lead to the belief in the existence of *one* norm, which in term can lead to self-judgment and competition [46]. This can work as a motivator [86], but it is important that the information is placed in context with each of the individuals, as a way to respect and support the diversity between people. A second, more concerning issue from privacy and ethical perspectives is *how* the data is processed. It normally depends on proprietary algorithms and often processing is performed on the cloud, obfuscating what is happening with the data. This issue is even more pressing when this can take place without the explicit consent of the users, or without understanding what consent implies. As a result, in most cases users lack agency over their own physiological data.

As technology advances and Physiological Computing devices become more ubiquitous, the expectations for literacy and transparency must increase. Both as a mean to this goal and as an end on itself [32], interaction between human and devices should have not only functional requirements but should also align with human values [60, 74], as they ascend from simple tools to communication partners [6].

To achieve this goal, our work is shaped by two main principles: (1) how communication takes place between people and the implicit contracts involved, and (2) the motivations behind interactions. Looking through these lenses, we focus on increasing the agency of users over the usage of their physiological activity. The result takes the shape of a simple, modular approach for the construction of physiological devices aimed at supporting both honest communication and intrinsically motivated activities [68].

This work is structured in the following manner: first, we introduce the *technical context*, including the surrounding domains, and the potential of tangibility to address some of the limitations. Then, we focus on humans, *how and why we interact* with each other, the role of artifacts in this process and the requirements for honest communication. The *physiological stacks* are then presented, as a bottom-up approach of creating explainable, modular physiological devices which design guidelines support honest communications. Since the devices are primarily targeted at prototyping and didactic applications, they are accompanied by a brief overview of *early feedback* gathered during focus groups with researchers, educators and pupils. Finally, we provide *examples* showing the potential of our approach for the creation of positive artifacts, with applications ranging from *introspection* to *play*.

Building on multiple disciplines, and rather than evaluating the effect of the artifacts on users, the overarching goal of this paper is to set the grounds for a conversation at a high level about physiological tangible technology.

2 TECHNICAL BACKGROUND

2.1 Physiological Computing and Affective Research

Physiological Computing [23] is an umbrella term referring to computational systems that use physiological signals as inputs. A close research field is Affective Computing [63], which focuses on the understanding and stimulation of human affect, with or without physiological sensing.

The potential of Physiological Computing arises from the richness and complexity of physiological activity. Externalizing this activity not only allows the owner to be aware of internal processes (interoception [16, 24]), but also supports the communication with others (people or devices), and the detection of patterns over time that would not be possible otherwise.

Physiological Computing faces many challenges, from **technical**, **design**, and **ethical** perspectives. From a technical standpoint, it is required to possess robust sensors, signal processing and state detection. In parallel to improving the technical tools, it is required to be able to design systems that do what is expected of them, which on itself strongly depends on the target application. From an ethical perspective, these systems deal not only with sensitive data but also with the capability of altering the users' internal state (sometimes without the user's awareness). For example periodic stimuli can induce changes in heart-rate [14].

2.2 From Quantification to Implicit Control

Physiological measurements are used in a range of domains and applications, each of them with different implications regarding processing, awareness and end-use.

Monitoring: Ambulatory systems monitor the user's activity over long periods of time, intervening only when necessary. This is predominant in clinical and sport environments.

Quantified self: One of the most common uses of consumer-grade physiological sensing is self-monitoring. The quantified self movement [82] refers to the phenomenon of "knowing yourself through numbers", by providing data agregation and visualization. Even when it can be engaging and foster reflection [12, 13], the benefits of such a representation has questionable implications regarding the abstraction of internal activity, as they foster self-judgment and competition. Some alternative approaches have been suggested, such as combining sensor data and self-reported data (semi-automatic tracking) [11], or the usage of Data Physicalization [83] where users build their own representations.

Biofeedback: An alternative to data aggregation is to provide real-time feedback of the physiological activity (biofeedback), in order to promote self-regulation [73]. This can not only inform users of their current state but also guide them towards a desired one. Such a technique has been studied since the 70s [87], particularly as treatment for anxiety [45, 66], or towards relaxed/focused states [30, 91]. The choice of representation affects how physiological activities are perceived and understood [49]. Real time biofeedback can alter the interaction between people, for example during playing sessions [25, 44, 54], or foster awareness of others' state, both people [50] and plants [51].

Active Control: Once physiological data is processed in real-time as part of an interaction loop, it can then be used to actively alter digital components. This allows the usage of the body both as a mean for interaction but also as a goal on itself [57], ranging from ludic to Assistive technologies. Research has been performed using breathing and brain activity to control VR games [2, 62, 79] with applications ranging from ludic to contemplative/meditative. Serious games sit at the intersection between ludic and assistive, such as the usage of breathing therapy for kids with attention-deficit or hyperactivity disorders [77, 78]. Assistive technologies mainly focus on the usage of BCIs (Brain-Computer Interfaces) [89] and muscle activity [81] to control prostheses and wheelchairs.

Passive Control: At the opposite end of the spectrum from Quantified Self, it is possible to use the users' internal state as an implicit control source, perhaps even without the awareness of the user; as a result, interfaces become *adaptive*. Examples range from ludic to functional. Ludic examples include Jenga [39], adaptive zombie games [18], VR lanscapes [65, 80]; when the adaptation is subtle, immersive spaces provide implicit biofeedback [3, 69]. At the practical end of the spectrum, neuro-adaptive technologies (i.e., based on brain activity) have been studied extensively for high-workload scenarios such as flight [8].

2.3 Physiological Objects and Spaces

In the past decade, there has been an explosion of artifacts involving physiological sensors, from simple objects to immersive rooms. Beyond the aesthetic and hedonic aspects of object design [35], exposure to real-time physiological representations can support interoception [55]. When our physiological and body activity is represented explicitly, in an overt manner, it can support communication and connection between people [10], and for that objects are an ideal medium.

From the HCI perspective, one of the main approaches used to allow users grasping complex and abstract concepts is the usage of Tangible User Interfaces [52], providing physical handles to digital information. Tangible interaction [37] includes not only object manipulation but interaction with "human rules", including spatialization and dialog.

Examples of devices combining Physiology and Tangiblility include *tangible puppets* to share heart-beats [4, 5], explore brain activity [26, 27], or customizable physiological representations [29]. Another alternative includes the usage of *wearables*, such as BodyVis, a body suit exposing physiological information [61], or Breeze [28], a connected pendant that supports communication via shared breathing as vibration. There are also *toys* such as Biofidgets [48], instrumented fidget spinners with their spin-rate linked to breathing and heart-rate variability. Another approach is the creation of ambient displays [88] that are always available and support exercises, such as Dišimo [56] and Inner Garden [69]. Some ambient artifacts take the shape or real size furniture, as Red Bench [38], or immersive-yet-minimalist rooms such as Sonic Cradle [85] and DeLight [92].

Given their complexity, these devices are challenging to build, customize or even understand, and their inner workings are usually hidden from the user. In most cases, at least part of the computations occur remotely, due to the complex signal processing pipeline required to extract meaningful features from physiological signals, that are noise prone. Yet, the form factor often indicates otherwise, masking that the device is leaking data. An example of this is Living Surface [90], an artistic piece that looks self contained but actually streams the data for remote processing.

As these devices deal with sensitive data, the lack of clarity becomes even more concerning. To answer this general problem of agency over the processing and appearance, tangible interfaces can take a modular form factor.

2.4 Modular Tangible User Interfaces

By decomposing an interface into its interacting components, it is then possible to support manipulation and customization, increasing control on the user's end. This principle has been used to support a variety of didactic or creative applications (i.e. for teaching or art). One of the earliest examples is their usage on tangible programming applications [52, 53], being better than their GUI counterparts for collaboration and engagement [36]. Another common usage of TUI is in relationship with sound synthesis and control. AudioCubes [72] are interconnected tangible bricks with both sensing and output capabilities. Similarly, reacTable [41] creates music based on the tokens' orientation and relative positions. As audio and physiological signals share similar signal processing pipelines, it is not surprising that the reacTable was extended to support physiological signals [15]. Modular electronics are another widely explored alternative, particularly in the domain of robotics [93] and STEM education, as with the littleBits[1], which propose a wealth of modules that can be programmed through Scratch [67]. BioToys [75, 76] support modular construction of muscle activity play-ware as biofeedback for rehabilitation, by instrumenting LEGO© DUPLO© bricks. MakerWear [42] is a modular electronic kit for garment customization, including a variety of inputs and outputs.

Once technical challenges are overcome, modular devices provide a scalable solution, which can reduce the inherent complexity of Physiological Computing devices [23]. This can ease the process of understanding and construction, increasing the users' agency. Beyond the technical considerations, Physiological Computing is affected by ethical implications, as devices extend their effect from tasks to people. To address this, we propose to shift their roles from tools to objects that explicitly take part in the conversation, that is to say from tools to "interlocutors", assigning them (and their designers) clearer responsibilities. Next section explores how such interpretation takes place and how it can guide the design of artifacts using physiological signals.

3 A DIALOG BETWEEN OBJECTS AND PEOPLE

It is possible to gain insight of HCI from human work activity [6]. The interaction loop, as any other activity, is an action mediated by *artifacts* (in the broader sense of the word, constructs for operation and communication) to achieve a goal. Motivations for these range from extrinsic (external cause) to intrinsic (internal desire from the user). Towards that goal, individuals communicate to coordinate and collaborate.

As Bødker states, a literal interpretation of Human-Computer Interaction observes computers as communication partners [6]. Then, when devices take the role of *interlocutors*, the dialog can be seen as taking place at two distinct levels: artifacts as constructs used as a *mean* to act and communicate, but also as *ends* themselves. A conversation then exists between human and device much like between humans, and in term, devices can also interact with each other (Figure 2). The potential of this is exquisitely explored in Victor's seminal talk *"the humane representation of thought"* [84].

As with other humans, our communication with devices happens at many levels and with diverse modalities. There are signals we create intentionally or unintentionally, other signals that we do not share, and we are not even aware of some of them. In some cases, others are aware of aspects about ourselves that we are not. This

[1] https://littlebits.com/

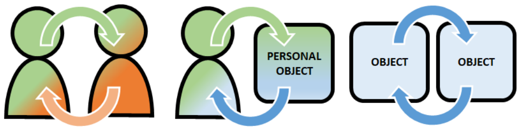

Figure 2: Communication and operation are always mediated via an artifact – let it be language, a physical medium, a tool, ... (here arrows implicitly involve artifacts). Artifacts can become dedicated interlocutors.

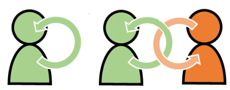

Figure 3: When considering implications for users, interactions can lead to intrinsically-motivated loops that support well-being. Interacting with the world and others becomes then a way to achieve self-satisfaction and self-fulfillment.

can be particularly true for emotional states, as people can observe subtle changes in facial expressions or cheeks blushing. Among the different ways we generate signals, the most relevant for this work are physiological signals that happen automatically. Some we can directly or indirectly control if we guide our attention to them (e.g. a change in breathing pace will also alter heart-rate), some are just a source of insight of our current state (e.g. perspiration). By including them as artifacts of communication and control, we gain not only new dimensions for interaction, but also the possibility of increasing our awareness over ourselves and others.

3.1 Intrinsically Motivated Interaction

Even when the description of HCI emerges from a purely functional view of technology, where devices are tools and sometimes coworkers, aimed at fulfilling a task [34], it is not limited to it. The interaction can have non-utilitarian objectives [32]; this can be achieved by considering the implications for the user instead of the task (Figure 3). This has been explored in depth in product design, as user experience is one of the main factors in product acquisition and engagement over time, and to which the *hedonistic* aspects play a mayor role [32]. For the users, this can be the end goal and not simply a secondary factor. Indeed, our relationship with objects can carry a deep affective value [20, 21], particularly when they react to our bodies [35]. Beyond the pleasure obtained from interaction, there is space for interaction that appeals and fulfils our intrinsic human aspirations [19] (*human flourishing*), such is the objective of Positive Design [22]. In the domain of digital technologies, this takes the shape of *Positive Computing* [9].

In that perspective, the Self-Determination Theory [70] points that three main psychological mechanisms involved in intrinsic motivation and decision-making (namely, *Autonomy*, *Competence* and *Relatedness*) play a critical role in the perceived quality of life/well-being. As such, it is important to consider fostering these elements by designing artifacts that allow users to better identify their strengths and weaknesses, improving their sense of autonomy and competence, while the usage of the technology allows the user to feel connected and appreciated by others. These mechanisms are contained in a feedback loop: their support leads to a virtuous circle, while ignoring them leads to their deterioration.

An important aspect of relatedness is how we present ourselves to others [31]. Digital media allow users to construct *avatars* and decide on the appearance themselves, supporting both autonomy and relatedness [7] .

3.2 Requirements for Honest Communication

Technological artifacts are designed, implemented, and interconnected (Figure 4). When we interact with an artifact, we interact with the intentions of the designer (up to the point where their skills allowed them to materialize their intentions), and could be potentially monitored by unknown devices and users. The intentions of users are combined via the device, much like when direct interaction between people takes place. This results in two main problems related to *transparency*: users' literacy and producers' honesty. Both these complementary issues reduce the users' *agency* over both their own data and the used artifact. In order to prevent the reduction of agency caused by transparency issues, we propose to frame the interaction with artifacts under the same expectations of honest communication between people, based on *understanding*, *trust*, and *agency*.

Understanding: Mutual comprehension implies a model – even when imperfect – of your interlocutor's behavior and goals, and a communication protocol understandable by both parts. Between the models we use to interact with people [64] and to interact with objects [59], there is a tendency to assign living properties to inanimate objects. This is both an opportunity for positive design [19], and a problematic source of dissonance if the interface breaks the trust of the user. To mitigate this issue, objects should be explicable, a property that is facilitated when each one performs atomic and specific tasks.

Trust: To ensure trust and prevent artifacts to appear as a threat, their behavior must be consistent and verifiable [31], and they should perform only explicitly accepted tasks for given objectives. It can be expected that the more a device is related to the intimate space of users' data and aspirations, the more they will feel betrayed when trust is broken. Hence users should be able to doubt the inner workings of a device, overriding the code or the hardware if they wish to do so.

Agency: As the objective is to act towards desirable experiences, control is important. As a first step, *Consent* is important, which cannot happen without understanding and trust. Then, the users should be capable to disable undesired functionalities, and to customize how the information is presented and to whom. Such requirement

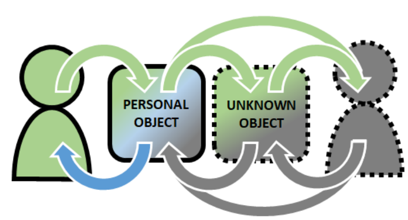

Figure 4: Due to their interconnections, our personal artifacts can be directly and indirectly affected by third parties without our awareness or consent. This includes their programming, and their capability to share or alter data in undesired/unexpected ways.

can be supported when objects are simple and inexpensive enough so that users can easily extend their behavior.

Building a system based around openness and trust should help users to avoid applications that are detrimental to them, as they would be more likely to know their purpose. Hence we advocate that endowing devices with honest communications also encourage positive and benevolent applications. In the next section we focus on the creation of our technical solution, which design requirements echo the requirements for honest communication.

4 MODULAR PHYSIOLOGICAL DEVICES

As an answer to the considerations gathered in the previous section, we designed, implemented and fabricated a tangible pipeline for Physiological Computing. This pipeline aims at easing the construction of transparent artifacts that support the communication for intrinsically motivated objectives. While the technical aspects presented in this section are not novel *per se*, they backup specific design requirements. These requirements enable users to control every aspect, distrust and modify the resulting devices, while learning the internal workings in the process. This way, they can not only understand but also challenge and override the designer decisions (Figure 4).

To ensure that the technology supports the desired requirements, we took a bottom-up approach, starting by the design of individual elements (atoms). Their combination allows the emergence of complex devices (Section 5), while preserving said requirements. We also used early feedback from discussions with specific user groups (researchers, practitioners, educators and learners) to iterate over our prototypes and gain insight about their possible applications.

4.1 Design Requirements

To achieve our objective of honest communications, we started by the following design requirements:

- **Atomic:** each brick should perform a single task.
- **Explicit:** each task should be explicitly listed.
- **Explicable:** the inner behavior of an element should be understandable.
- **Specific:** each element capabilities should be restricted to the desired behavior, and unable to perform unexpected actions.
- **Doubtable:** behaviors can be checked or overridden.
- **Extensible:** new behaviors should be easily supported, providing forward compatibility.
- **Simple:** As a mean to achieve the previous items, simplicity should be prioritized.
- **Inexpensive:** to support the creation of diverse, specific elements, each of them should be rather low cost.

4.2 Approach

First, a modular design was selected, as it supports *Atomic* and *Specific* interconnected elements. The internal behavior (Figure 5) is supported by standard electronics and Arduino microcontrollers; as a result, each atom is *Explicable*. Together, these three requirements help users to understand how the devices work. Since it is possible to use a programmer to verify the checksum of the binary code, or to simply override it, the technical implementation *Allows Doubt*, which in turn help to bring trust to the functionalities that are *Explicitly* labelled. This labelling is facilitated by *Simple* individual actions. Each atom is placed inside a 3D printed case, *Inexpensive* to fabricate (each brick costs between 5-25€, depending on the functionality). Because users can easily replicate, customize and *Extend* a brick, and because they can choose to assemble atoms however they like, they have agency over the entire system.

The electronics are comprised of off-the-shelf components. Computation is performed using an Arduino Pro-Mini micro-controller board (ATmega328), they can be programmed using standard Arduino IDE and Libraries. the selected micro-controller has a low price, but lacks a programmer so it must be programmed using an external programmer.

In order to keep the communication between atoms *Simple* and *Explicable*, we opted for analog communication at 1kHz sampling rate (sufficient for most physiological signals, including electroencephalography). For cases were the data needed to be digitized for communication, no additional meta-data is shared outside a given atom unless explicitly stated. By using this hard constraint, the design is *Extensible*, rendering possible to create new atoms and functionality, similar to the approach used for modular audio synthesis. Analog communication also allows the interfacing with standard controllers (see Section 5). A side effect of analog communication is its low bandwidth, and sensitivity to noise: we accepted these as we consider the gain in transparency is worth it. It can be argued that this approach leads to a naturally degrading signal (akin to a *"Biodegradable biofeedback"*), ensuring that the data has limited life span and thus limiting the risk that it could leak outside its initial scope and application.

In order to build a device, bricks are stacked, creating custom explicable devices. The signal travels upwards, while some bricks allow the additional connection via cables (initially via protoboard wires, then improved to use standard audio cables with 3.5mm jacks).

4.3 Explicit Iconography

In order to explicitly inform users, we established labels (Figure 6) to notify them what type of "dangerous" action the system is capable of performing. A standard iconography was chosen to represent basic functions (e.g. floppy disk for storage, gears for processing, waves for wireless communication, ...). We consider that, similar to food labeling that is being enforced in some countries, users should be aware of the risks involved for their data when they engage with a device, and thus being able to make an informed decision. A step further could be taken by reporting that a device *does not posses* a given functionality, akin information about allergens. These labels include:

- **Sensing:** When data is being captured, and which type (overt or covert).

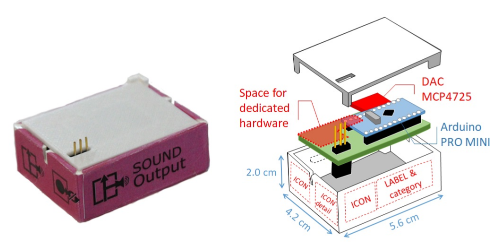

Figure 5: Brick atom, interior, and labeling.

- **Processing:** The data is – or could be – altered.
- **Output:** If and how the signal is being displayed (overt or covert).
- **Sharing:** if the information is being shared and with whom (known pair, any pair with password, anybody).
- **Storage:** if storage takes place, which type (with expiration, without expiration).

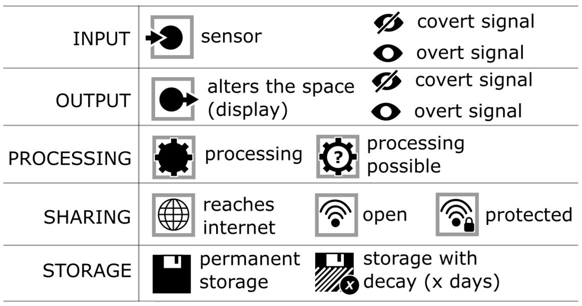

Figure 6: The icons, and their meaning.

Figure 7: The created bricks, sorted by functionality. From left to right: power supplies, inputs (breathing, heart-rate, movement, ...), processing and merging, communication (analog, Bluetooth, serial, ...), and output (light, sound, vibration, ...).

The measurement of breathing with a brick connected to a belt placed around the chest would constitute an example of overt sensing; covert sensing would occur if breathing is measured instead when the brick is being held against the chest, through an inertial measuring unit concealed inside it. As for output, vibrations would convey a covert feedback since only people holding the brick could feel it, while the use of LEDs would create an overt feedback, visible by all those around.

4.4 Supported functionalities

The functional atoms were divided in: input, processing, storage, communication, output, and power (Figure 7).

Input: Three main input modalities are supported: signal synthesis, analog sensors and I2C sensors. The analog approach is used to obtain breathing via an analog stretch sensor, while I2C sensors are used for Heart monitoring via PPG (PhotoPlethysmoGraphy) and for 9DOF (degrees of freedom) inertial measurement unit.

Processing: Signals can be also processed via individual functions, that can in term be controlled with analog parameters. Each of these bricks can be easily reprogrammed. Currently, supported functionalities include signal smoothing, thresholding, beat detection, signal inversion. As parameters are also analog, it is possible to use the output of one stack as parameter; this is particularly useful to perform merge functions, such as coherence and average.

Storage: Peripherals support the storage and replay of information from an SD card.

Communication: Communication between stacks can be performed using Bluetooth Low Energy (BLE), with different degrees of security. Paired BLE bricks can talk only with their pre-assigned couple using MAC filtering, while open BLE bricks accept connections from any device knowing the password. We envision that RFID stickers could be used to explicit paired dongles and enable asymmetric encryption over Internet. Alternatively, communication can be performed via analog signals, similarly as how it is performed internally in a stack. Finally, Bricks support serial communication with computers and with each other. Later iterations include dedicated analog adapters (Section 5).

Output: Each output brick has dedicated hardware and software. Supported output modalities include light (RGB LEDs), sound, vibration and actuation.

Power Supply: 5V power supply that can be charged via micro USB, provided by an Adafruit PowerBoost 1000C and a 700mA LiPo battery. Bricks are designed to share power in parallel, so a power supply can be placed at any point in the stack.

4.5 Early feedback

During the conception of the bricks we used early feedback gathered with different groups to iteratively explore and improve the quality of the solution from three axes: technical, practical, and didactic. Seizing opportunities at hand, three informal discussions were performed in groups of between 4 and 12 individuals, with a duration between 30 and 90 minutes. Each time, the group was introduced to the concept of modular physiological devices (5 minutes) and then progressively presented the functionality (10 minutes), and finally the participants were allowed to experiment with the bricks for the remaining time, invited to think-out-loud. We report below a selection of the main points that were raised during those sessions. As the objective of this paper is to present the rationale and vision behind the physio-bricks as well as a first set of functionality, a proper evaluation of how people would use those devices in more ecological settings was relegated to future work.

Experts in Physiological Computing: they were approached during an event dedicated to BCIs. The first iterations over the technology were informed through discussions via demonstrations during the Cortico '19 conference in France. This took the shape of discussion groups that started with a formal presentation of the project (4 groups, 30 minute each, 26 total participants, including clinicians, BCI and neurofeedback researchers). The most common remark was that the modular approach was found to resemble OpenViBE[2], a visual programming environment aimed at creating BCI applications. For that reason, the concept was well received, particularly as a potential didactic tool to explain the underlying architecture of such applications. It was also often mentioned the desire to observe the signal at different stages of the processing

[2]http://openvibe.inria.fr/

pipeline, as well as to be able to control the processing modules – two features that we eventually implemented. Finally, some expressed an interest in bridging the bricks with computer software, for example to perform more heavy signal processing. For this community transparency and agency were not considered as important aspects of the system until we explicitly introduce them.

HCI researchers and designers: the bricks were presented to colleagues during two focus groups, one conducted at our research institute (Inria Bordeaux) with HCI researchers (12 participants); another conducted at Ullo, a private company specialized in biofeedback applications that collaborated on this project (9 participants). While most participants were aware beforehand of the existence of the project, they discovered the bricks during the focus groups. From the designers' perspective, the bricks were a good tool to brainstorm/create prototypes, and then move that to single integrated devices. With a similar use-case in mind, researchers mentioned that the low cost is a positive factor to allow deployment and evaluation in the wild. Improvements for the casing were recommended, using rectangular or cylindrical shapes and LEGO© or magnet connectors. The interfacing with other devices was considered of interest – particularly standard controllers, computers and phones –, as well as the use of ambient sensors (e.g. microphone) and the capability of measuring signals from animals or even plants. Finally, it was common for the participants to envision the encasing of the stacks in more appealing exteriors (such as plush, toys, and wooden artifacts).

Primary school teachers: a group of 5 teachers and 1 scientific outreach educator was invited to experience and discuss the bricks while they were visiting our research institute. After a short introduction of the project, they were prompted to react about the technology and the possible usages. For teachers, the didactic aspects of the technology and well-being applications were the priority. They compared it to similar open projects used at schools, suggesting a maker approach where students could build their own bricks as a mean for learning activities, with the beneficial effect of learning about their physiology. With a more explicit focus in well-being and introspection, it was discussed that physiological connected avatars could be used to measure and regulate the overall class state before starting a lesson, allowing to perform either relaxation or focus exercises.

Pupils: As part of an outreach event that took place in a French school, we presented the bricks to 16 pupils (11-12yo), divided in three groups. Upon entering the room the pupils would take place around a table where the bricks were gradually introduced. In general pupils were very engaged into exploring and experimenting the bricks. The different modalities led to radically different reactions. In one instance, while testing the bricks, it happened that the feedback was not provided to the sensed user, but only to those around (through audio with headphones, or through vibrations). It resulted in an awkward situation where the user wearing the breathing sensor felt like being judged. This event highlights the importance to carefully consider the use-case scenario to avoid discomfort. Interacting with pupils was also a reminder that we need to carefully explain how the provided feedback is only an interpretation of the physiology, and not a direct representation (as with synthesized audio output and breathing: no, the belly does not sound *that* funny). From a technical standpoint the bricks in their current form proved to be robust enough for their manipulation, albeit with pupils who were mostly gentle. When asked what elements were missing, pupils wanted moving objects (actuation), sensors for temperature, and game control.

5 EMERGING DEVICES

The simple functionality supported by the bricks allows users to construct their own artifacts for communication in an explicit manner. The devices support generic input, processing and output capabilities, yet the support for physiological signals renders them more intimate.

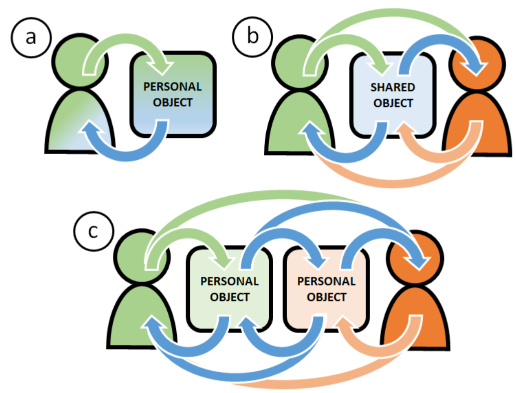

Figure 8: Communication with/via objects: (a) object as interlocutor, (b) shared object and communication around it, (c) direct and indirect communication via personal objects.

Interaction with and via objects can take different forms. For instance, the interaction with the object can be the end goal (Figure 8-a): an interlocutor (human/object) can feed back information using a different modality and after processing it, or at another point in time. A shared object can act as an additional communication channel between two persons (Figure 8-b), or each person can have a personal object connected to the network (Figure 8-c). Incidentally, Figure 8-c shares similarities with Figure 4, yet with our approach the user can also have the designer role.

To showcase the potential of emergence of complexity and richness from simple atoms, we created a set of proof-of-concept devices, inspired by the literature, and focusing on supporting principles from Self-Determination (Competence, Relatedness, Autonomy) [70] and Positive Computing (Enjoyment, Engagement, and Empowerment) [9]. Note that despite the fact that current implementation of the Physio-Stacks are somewhat bulky, the bricks can already be used to build functional systems. At the core of this project, we were actually driven in part by the possibility to recreate most of the past works combining physiological computing and tangible interaction that we have been developing over the last years.

5.1 Physiological Introspection

Tangible Physiological devices for introspection have been explored in the literature (e.g., [5, 29, 69]), frequently in the shape of a literal or metaphorical externalization. In this line, we used the bricks to create a customizable avatar that can display the user's current breathing patterns in real time using one or more modalities (biofeedback).

To ease the customization of the displays, we constructed stackable, LEGO©-compatible NeoPixel[3] bricks (Figure 9). These bricks are a reduced scale of the standard atoms, connected using standard LEGO©snaps and reinforced with magnets, and 3D printed using a Formlabs Form 1+ for the required increased resolution. Given the size it is not possible to add a micro-controller, and for this reason they need to be connected to a stack as previously presented.

By adding a recording brick to the processing stack, the device allows the user to replay sessions later on for introspection and monitoring. A single recording brick can also work as a *cassette*, a physiological snapshot allowing you to track yourself over time, or alternatively could be physically shared with others.

While this application was very much inspired by one of our previous project, Tobe, where we used spatial augmented reality to build tangible proxies for physiological activity [29], the PhysioBricks brought more versatility to the design and facilitated the construction of the devices.

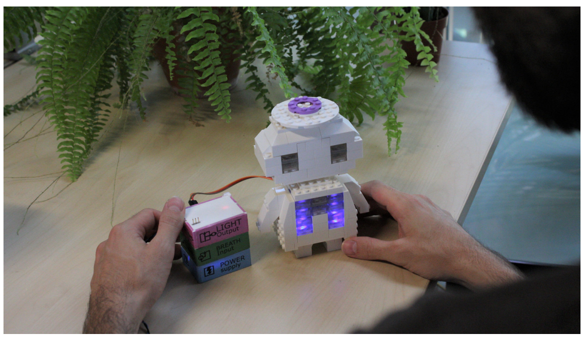

Figure 9: The avatar can be used as real-time multi-modal biofeedback, or to observe recorded sessions. Given that it is compatible with construction bricks, it can be easily customized.

5.2 Physiological Communication

To allow the communication between people, it is possible to explicitly send signals via Bluetooth. We assembled an artifact (Figure 10) that reflects heart activity similar to [5]. The signal is provided to the source user via vibration (covert), and can be optionally and explicitly be sent to a LED orb (overt). As the captor requires contact, the usage of the communication artifact must be intentional, requiring the user to focus their attention. If desired, the Bluetooth streaming brick can be physically removed, keeping the local feedback unaltered, and private. By design, users can exchange the physiological sensor, or alter the signal received/sent with custom processing, or use a different output modality. This flexibility also fosters the communication beyond the device, as verbal/nonverbal communication takes place of how and when the information shared changes. It is easy to envision a version of the system comprised of two symmetrical devices that send the physiological activity to the remote counterpart, as we did in [28], allowing to display both the local and remote signals in any desired fashion, or to combine them via merge bricks.

[3] Adafruit NeoPixel https://www.adafruit.com/category/168

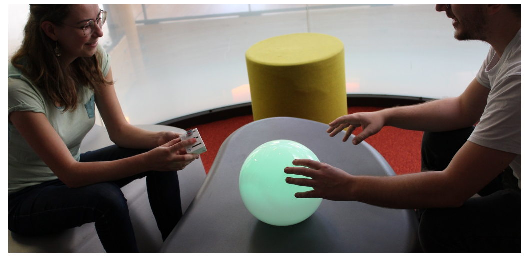

Figure 10: A person uses a brick stack to explore their heart activity via vibration (left) while also streaming the information to a light via Bluetooth (right orb).

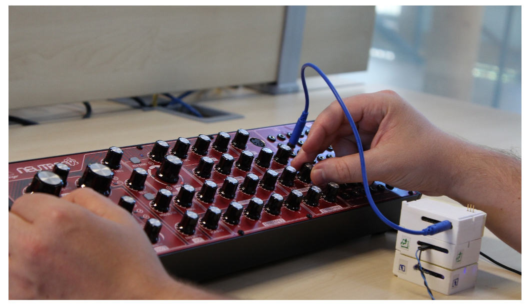

Figure 11: The bricks can be connected to analog synthesizers, to create physiologically influenced music.

5.3 Physiological Creation

The construction of physiological devices using a modular approach is on itself a creative task, yet one of our main inspirations for the design was analog audio synthesis. As a first step, the bricks provide audio generation using Pulse Width Modulation (PWM) and the Mozzi library[4]. This provides a simple output, yet the associated low fidelity gathered mixed feelings during the focus groups. To create a richer, more expressive experience, we connected the bricks with an analog sound synthesizer (Behringer Neutron). This supports the experimentation and creation of music using physiology, while also allows users to explore internal parameters using other modalities (Figure 11).

5.4 Physiological Play

Games are important [40], as they tap core elements of self-determination [71]. The action of play is also innately human [43], and it was expected that pupils would mention such usages during the focus groups. Physiological data has been used to enhance play [1], and, in the context of serious games, for healthcare [17, 77]. Using stacks, it is possible to support such activities. The bricks support direct communication with a computer via Bluetooth or USB, yet in order to be able to interact with programs a protocol must be explicitly created. Instead, we opted for interfacing with the Xbox Adaptive Controller (XAC)[5].

Interfacing with the XAC is a straightforward task, as analog communication is already supported and only a signal remapping is required (from [0,5v] to [0.3,1.3v]). As a result, it is possible to control any game using a combination of standard controls and

[4] https://sensorium.github.io/Mozzi/

[5] https://www.xbox.com/adaptive-controller

physiological signals, both actively and – for games that support it – passively. This aligns with the philosophy of the XAC, allowing to customize each input of the controller; the bricks then enable the construction of a custom physiological input parameter, which in term allows the adaptation of the software side of the interface too.

To show this, we created a custom direction control for ABZU [6], a beautiful diving game. Breathing at a slow deep rhythm (recommended for diving) allows the player to move forward.

Figure 12: By connecting a stack to the Xbox Adaptive controller, it is possible to have immersive gaming experiences.

Multiple signals could be connected to a single controller, and even be preprocessed and merged using the bricks. This can be used for simultaneous breathing exercises, such as in [77], or more playful experiences such as games synchronized to the players' heartbeats. This is similar to how some games support two users using a single controller (*"split controller"*, as in Overcooked[7]), that can be said to create human connection out of the virtual space.

6 DISCUSSION

6.1 Technical Aspects

From a technical standpoint, the current design is presented solely as a first step towards initiating dialog about transparency, tangibility and positive computing. We believe the simplicity and constraints generated by the current approach render it easier to refine and improve the system over iterations, yet address our key concerns of our work *by design*.

While the current subset of physiological sensors implemented in this specific project is limited to breathing and heart rate, two sensors that are already sufficient to explore the system in social setting and see the emergence of rich interactions [28, 29], we are in the process of adding electrodermal activity, muscle activity and brain activity (through existing headware) as additional input. Combined with new output (heat, scents), these developments can be use to broaden the range of applications – e.g. emotion regulation, neurofeedback.

Regarding security, the current concept implementation focuses on explicitly exposing the risks of a given functionality, while constraining the hardware capability to the minimum required. This provides a level of safety, but also reduces the impact ill-intentioned software. Communication protocols are kept simple and un-encrypted, and protected via hardware when possible (direct analog communication, MAC filtered Bluetooth). That said, the support for reprogrammability implies that a given atom could perform unexpected actions, and to that, the user has the possibility to inspect and change its behavior (rendering trust *explicit*), or to add additional layers of software encryption if desired.

It is possible to interface with other systems in a straightforward manner. Mobile devices are supported via Bluetooth, and desktop applications can use either Bluetooth, custom serial protocols or interfacing with standard controllers. As game development kits are easily supported (e.g., Unity3D[8]), the development of adaptive extended reality (XR) applications is possible, yet the form factor should be reconsidered.

Regarding the electronic circuitry, it is currently created over pre-perforated PCBs for ease of modification. Yet, the standard micro-components come in different form factors. It would be possible to run the same software on surface-mounted electronics (SMD, smaller yet fixed) and socket-mounted microchips (DIP, bulkier yet exchangeable). The decision about which to use depends much on the final objective (between compact objects that require higher expertise to build, and *doubtable* and didactic atoms).

The current design is based on simplicity, clarity and readability, using 3D printed cases with printed paper wrapping. This could be greatly improved with better materials or more organic shapes, the same way we aim for behavior control, we would like to support appearance customization.

6.2 Design Aspects

Some of the design requirements might not be of equal importance depending on the use-case, and they could even prevent some specific applications. For example, the *atomicity* of the system leads to duplication and goes against miniaturization or even *inexpensiveness*: whereas one micro-controller could at once perform measurements, processing and handle the feedback, each function is here fulfilled by a specific brick. On the other hand, the open nature of the system makes it possible to bypass such limitations if users choose so. Ultimately the freedom is theirs to adhere or not to the design requirements, depending on their goals.

In other instances it might be difficult for some target users to fully grasp all design requirements. For example young children might not be able to *doubt* the devices if they don't know how to (re)program them. But even then, the decision to use the Arduino platform helps to lower the entry barrier for programming, and, as the platform is evolving, we plan to further reach for education settings by creating bridges with the Scratch programming language[9].

At a higher level, the design of the functional atoms and their combination into Physiological Stacks was conceived as a mean to support the connection with ourselves and each other, and reaching out towards what moves us. The main driving force was to support the creation of physiological artifacts with a subjective value and meaning (*qualia*): we aimed towards the creation of *Qualified-Self* devices.

Between the Subjective and Objective perception, there is the Collective. It is worth noting that one of the core influences for this work was *totemism* [47], partially in the physical sense, but mainly in the ontological sense defined by structuralist anthropology: a symbolic system defining culture through nature. Metaphors

[6] https://abzugame.com/
[7] https://www.team17.com/games/overcooked/
[8] https://unity.com/
[9] https://scratch.mit.edu/

constructed out of physical world elements that group and guide individuals. Each artifact represents one or more aspects of a single or group of individuals, reflecting their internal state. These externalizations and group representations can be used as guides for reflection, and intermediaries for communication.

As the devices are influenced by the users' inner workings, people quite literally breathe life into their creations. We consider that *animism* (the human tendency to perceive life between the realms of animate and inanimate) is not to be disregarded, and instead should be used as a design principle. According to Nietzsche [58], animism is an atavism: reappearing even when lost, making it intrinsic to our cognition, and perhaps even useful. As we perceive and connect with artifacts at a level distinct from purely rational, designing them to respect and support our values and aspirations is a way to use this characteristic positively. We present this work as a step in that direction.

7 CONCLUSION

In this work, we presented a tangible modular approach designed to ease the prototyping and understanding of physiological devices, and their use to supporting positive applications. This technology is influenced by multiple research areas, including Physiological Computing, Positive Computing, and Tangible Interaction.

To address the critical ethical aspects of physiological devices, we focused on how and why humans interact with each other, and framed interaction with objects under the same expectations of honest communication between people. The resulting modular bricks serve both as a prototyping toolkit for the construction of physiological devices, and a didactic tool to explain the underlying technology through problem-solving. To be consistent with our design requirements and ensure transparency and trust, the core hardware and software related to those bricks are published as open-source: https://ullolabs.github.io/physio-stacks.docs/.

The design requirements behind the Physio-Bricks result from a combination of literature review; our own experience over the last 8 years creating, experimenting with and teaching about devices using physiological signals; and informal conversations with various researchers, designers, artists, private companies, enthusiasts, or lay users. While these requirements should favour honest communications, such causality was not tested experimentally. Another major limitation of current work is that we did not investigate up to which point a design aimed at honest communication would truly lead to positive applications, that benefit end-users. The next step will consist in properly investigating these hypotheses, as well as conducting semi-structured interviews to understand how users perceive aspects such as control, freedom and privacy once they are manipulating the Physio-Bricks.

By aggregation of simple functions, it is possible to build rich and complex behaviors. This was showcased by constructing and reproducing Physiological Computing devices that allow the creation of music, playing games, or the communication with others and ourselves. During the iterations, the technology was presented to diverse focus groups (from experts in physiology to pupils). In the future, we plan to create kits that allow users (including children) to create custom devices and learn simultaneously about electronics and their physiology.

We hope the approach will spark discussions around physiological devices and help to steer their usage toward more benevolent applications, centered around users.

8 CONTRIBUTION STATEMENT

As the project involved a multidisciplinary team, and in the spirit of honest and transparent communication, we consider relevant to explicitly list the individual author contributions.

Author	Contribution
Joan Sol Roo	Discussion, Concept, Fabrication, Applications Writing
Renaud Gervais	Early concept, Modular LED LEGO©
Thibault Lainé	Discussion, Electronics and Fabrication considerations
Pierre-Antoine Cinquin	Discussion, Human and Social considerations
Martin Hachet	Project coordination, Funding
Jérémy Frey	Discussion, Concept, Applications, Writing, Funding

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