Multi-sensory Wearable Bio-feedback Pillow to Enhance Genuine Feeling of Intimate Connection

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Figure 1: A hugging couple wearing *Lokahi* device.

ABSTRACT

As human beings, we are designed to be empathic, to connect emotionally with each other and to share affection. This is part of our nature and makes us feel like part of a group. New forms of technology enable us to share, in real time, a variety of data. Some data, such as those on heart rate, can relate to our affective state. This research focuses on asking if technology-mediated interactions might help us to feel more emotionally engaged and intimately connected, especially when sensorial feedback about our inner state is provided. In this context, we present an interactive device that provides two users, through pulsing lights, with feedback on their heartbeats and the related level of synchrony (fig. 1). The prototype could be used to assess the effectiveness of this technology and to improve the feeling of connectedness and intimacy between two users.

CCS CONCEPTS

• **Human-centered computing** → **Wireframes**; **Haptic devices**; **Interaction design theory, concepts and paradigms**; **Interaction design theory, concepts and paradigms**; **User centered design**.

KEYWORDS

biofeedback, emotional engagement, intimacy, wearable computing, interactive technology

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1 INTRODUCTION

Sharing physiological signals belonging to the emotional sphere through technology-based biofeedback techniques could facilitate interpersonal communication. Indeed, these signals can provide indirect clues about our intimate feelings. Biofeedback is a training technique in which people are taught to adjust the functioning of their autonomic nervous system by using signals from their bodies. Nowadays, biofeedback is widely used to support both well-being (e.g., through mindfulness meditation and relaxing exercises for stress management) and also therapeutic activities (e.g., through psychophysiological intervention to treat disorders such as anxiety and depression) [7, 12]. To a small extent, recently biofeedback has also been used in the area of entertainment, such as art performance and gaming [8].

In the context of Interaction Design, this *Work in Progress* (WiP) focuses on a novel use of biofeedback to convey clues about our inner feelings and share them with people. This could be used to improve awareness of our own feelings and emotional understanding of each other. Here we propose to explore the interaction design space of *expressive biofeedback* by presenting a technology-mediated way to make two partners share information about their heartbeats. This is done through the use of *Lokahi* . This is a soft wearable prototype designed to provide an intimately emotional experience of closeness between two people. This wearable could hence be explored as a means of enhancing social connectedness and empathy, and to reduce stress. *Lokahi* has a shape designed to encourage hugging, a touch-based behaviour that elicits positive and reassuring feelings [4]. The embedded electronics of *Lokahi* allow the users to visualise their heartbeats through sensors and pulsating coloured lights. In this way, the users can become aware of their own and each other's inner state. Moreover, the hue of colours blends according to the synchronisation of the two heartbeats thus producing interesting visual feedback on it. We propose that such information, along with the haptic feedback, can potentially create an interesting, interactive loop between the users. This is expected to improve their feeling of connection and create a shared experience of intimacy (*Lokahi* means *harmony* and *balance* in the Hawaiian language). We call this experience as *co-feeling*, which means *experience of feeling together*.

The proposed prototype is an enhancement of a previous authors' work [9] encompassing several design improvements to overcome relevant functional limitations. Thanks to these improvements the current device version is now ready for experimental testing with human participants.

The rest of the paper is organised as follows: in sec. 2 we give a brief overview of works where technology is used to analyse and promote social connectedness; in sec. 3 we provide details about the new prototype, describing the new design features, the improved hardware and software for heartbeats synchrony feedback, and the related control App; in sec. 4 we provide the result of a feasibility test, proving that the device works as expected and is then ready for a pilot experiment involving pairs of participants; finally, in sec. 5, we propose a possible extension of the work, suggesting new pilots and hardware improvements, including new sensors to enrich the feedback for the users.

2 RELATED WORKS

The topics of *Social and Emotional Connectedness* and biofeedback effectiveness are analysed in many, often interrelated, works. In [13] the authors review several high-tech systems designed to support – through a technological mediation – the *feeling of connection*, a desired aspect of the social interaction which is common to all human cultures. In [8] the authors present a review of systems that provide users with live biofeedback for everyday use. In [10] it is shown how physiological synchrony is associated with attraction in a blind date setting, while [1] analyses the relationship between the experienced emotional states and the level of physiological synchrony.

Interestingly, many works which present technological prototypes for real-time emotional feedback (whether alone or socially shared), highlight also the importance of the design process in realising the proposed tools; in this context, the design, including aesthetic consideration, is critical to providing meaningful and relevant experiences to the users (*User Experience*). Some of the interesting related works are (1) *Breathing Scarf*, a sensorised, fibre optics-equipped, wool scarf, conceived to promote emotional self-regulation of the wearer in mindfulness activities focused on breath control [2]; (2) *Us*, a set of two wireless-connected wristbands, developed to enhance the empathy of romantically engaged couples, by sharing their emotional arousal [11]; (3) *Breeze*, a wearable pendant providing multi-modal biofeedback of the wearer's breathing pace, a signal which could be used by loved ones to promote connectedness in remote communication [3].

3 DESIGN AND TECHNICAL FEATURES OF THE NEW PROTOTYPE

In a previous work [9] we proposed *Lokahi* , an interactive wearable pillow, designed to promote an intimate interaction between two partners and heart-to-heart entertainment. The device, equipped with two pulse oximeters, could show to the users their heartbeats, through pulsing, coloured lights. In this work, we improved several design and technical features, advancing the previous *proof of concept* to a reliable device for testing and data collection[1]

3.1 Form and Function

Concerning the previous prototype (fig. 2, top), the shape of the body pillow was partially re-designed to overcome some ergonomics challenges (fig. 2, bottom). The new design lets the two users hug each other while maintaining the wearable's pockets holding the sensors and the lights in a comfortable position. As shown in the figure, each partner can hug the other and adjust his/her hand position to better detect the light output.

The current prototype is realized to enhance relaxing haptic sensation with the use of soft, pillow-like furry fabrics. Users can touch, hug, wear and freely place *Lokahi* where/how they desire. Thanks to its current user-friendly design characteristics, users can have more freedom and fun while experimenting with innovative ways of interacting with other users of *Lokahi* (fig. 2, bottom). Therefore, the newest version provides more possibilities and advancements to experiment with its main objectives.

[1]A brief demo video of the new prototype is available at the link https://drive.google.com/file/d/1iXtZTIxaVGkb3Un5sRnW51xlZe65rdEJ/view?usp=share_link

Figure 2: Evolution of *Lokahi* design. Top: the first version of the device *Lokahi* . Bottom: the current design improves the usability of the device as the new shape allows users to place *Lokahi* freely on the body, to observe the visual feedback easily.

3.2 Hardware specifications

The embedded electronics of *Lokahi* has been improved. The board is now based on a commercial ESP32 board [2] which provides BLE Bluetooth wireless connectivity and nice computational performance. Two professional pulse oximeters [3] are used to detect the users' heartbeats: the sensors, supplied as finger-clips, are embedded in the *Lokahi* 's pockets. The sensors provide an analog input reflecting the blood volume variations measured on the fingertip, which are directly related to the heart rate (*photoplethysmography* or PPG). The visual feedback is produced through two addressable LEDs strips (one per user), each equipped with 20 LEDs. The first 10 LEDs will mirror the heart activity of the first user while the second 10 LEDs will reflect the activity of the second user. The device is powered with a 3.7V LiPo battery, which can be easily recharged via a USB cable.

[2]https://en.wikipedia.org/wiki/ESP32
[3]www.pluxbiosignals.com/products/blood-volume-pulse-bvp-sensor

For each user, the PPG sensor and the LEDs strip are assembled in the *Lokahi* pocket. In this way, the user can easily see his/her heartbeat and the partner's one.

3.3 Android App

Compared to the old prototype, an Android App was developed both to monitor the sensors reading and save the data in a log file for subsequent analysis. The App was implemented with *Godot*, an open-source graphic engine for game development. Thanks to a custom plugin[4], the App can receive data in real-time from *Lokahi* via a Bluetooth connection. The App GUI is shown in fig. 3, and

[4]https://github.com/IM-TWIN/BLE-Android-Plugin

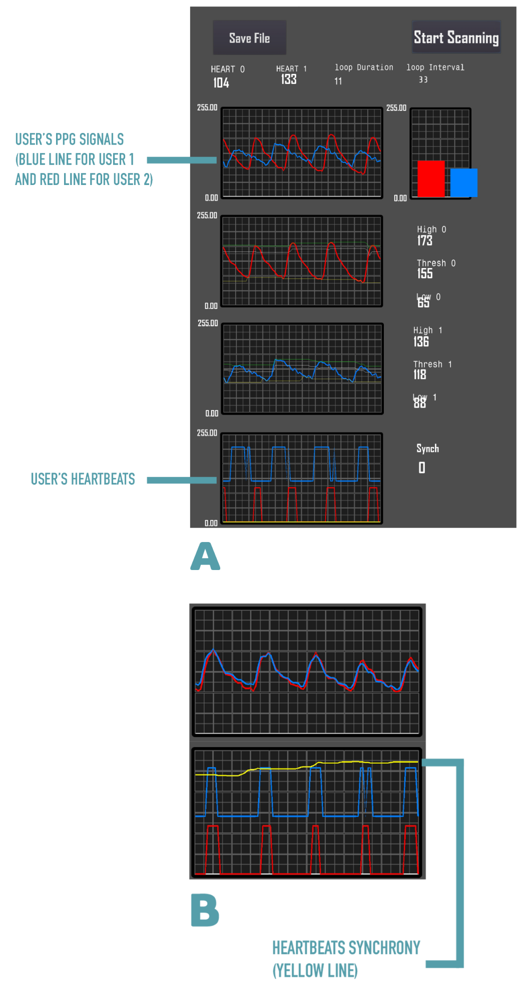

Figure 3: A: the screenshot of the App GUI; the App shows the raw PPG data, the detected users' heartbeats, and the level of their synchrony; in this example, two non-in-sync users were tested (yellow line close to 0). B: an example of the App feedback when the signals are synchronised (yellow line close to 1); data obtained with one user testing both PPG sensors and showing maximum sync.

provides the users with their heart rate information and the related synchrony level.

3.4 Computations supporting the display of the heartbeats and their synchronisation

Lokahi 's display of the users' heartbeats and their synchronisation, by means of pulsing lights, is based on the following computational operations which combine 3 equations used to drive the two LEDs strips.

Each PPG analog signal (one signal per user) is read at 30 Hz by the ESP32 as a number in [0, 4095]. The signal is then filtered to obtain a binary value y in $[0, 1]$, being 1 the detection of the signal upper peak (i.e., the heartbeat), thus producing a cyclic square wave per each user. y is finally filtered by a Leaky integrator function[5] with temporal parameter $\tau = 2$, which produces a signal u:

$$u_t = u_{t-1} + \frac{1}{\tau}(-u_{t-1} + y_t) \tag{1}$$

Eq. 1 produces a smooth continuous value in $[0, 1]$ that gently increases when $y = 1$ and gradually decreases when $y = 0$ (see fig. 4). The two signals related to the two pulse oximeters are denoted as u^a and u^b respectively for user a and user b. Note that the Leaky signal filtering is due solely to aesthetic reasons: indeed, u^a and u^b are used to obtain pleasant pulsating lights, as explained in the next lines.

In order to compute a signal s reflecting the synchronisation between u^a and u^b, we first compute the *mean squared error* (MSE) between two vectors containing the last $L = 300$ values of such signals. Given that sensors are updated each 33 ms, the vectors contain data for 9.9 seconds. The MSE is close to 0 if the two vectors are roughly equal and overlapping, and positive otherwise: the greater the difference between the two arrays, the greater the value. The value s in then normalised in $[0, 1]$, fixing an arbitrary maximum threshold $\alpha = 0.2$, observed when the two signals are reasonably different [6]. Formally, s is computed with the following equation:

$$s = 1 - \left(\frac{1}{L} \sum_{n=1}^{L} (u_n^a - u_n^b)^2 \right) \cdot \frac{1}{\alpha} \tag{2}$$

[5]https://en.wikipedia.org/wiki/Leaky_integrator
[6]This was done generating random noise on both sensors.

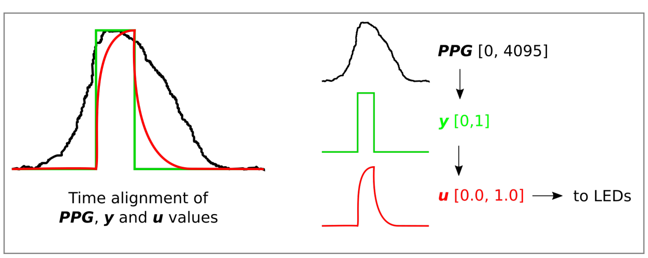

Figure 4: The PPG value is filtered by a Leaky function, to obtain a continuous *u* value in correspondence of the heart peak *y*; *u* is then directly used to drive the LEDs with a pleasant, smooth aspect, when an heartbeat is detected.

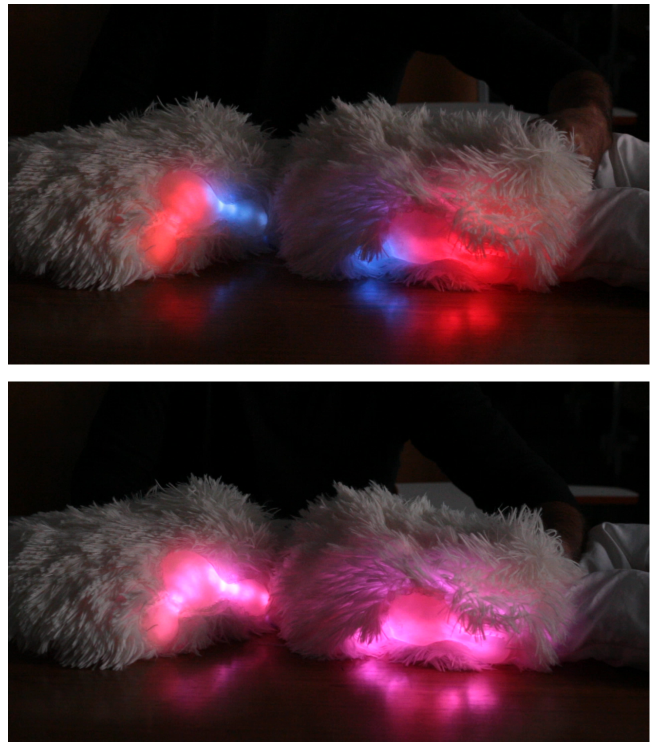

Figure 5: *Lokahi* visual feedback. Top: the 2 lights are respectively red and blue when the users' heartbeats are not in sync. Bottom: both lights blend into magenta when the hearts beat in sync.

Note that the temporal extension of the signal vectors (9.9 seconds, during which at least about 5-6 beats are detected) was chosen to minimise possible erroneous detections of synchrony due to single heartbeats happening at the same time by chance[7].

The RGB components for mastering the 2 strips LEDs colour, mirroring the heartbeats, are finally computed using a combination of eq.1 and eq.2, i.e., integrating the variables u^a, u^b, and s, as shown in eq. 3:

$$colour\ u^a = \begin{cases} red = u^a \\ green = 0 \\ blue = s \cdot u^b \end{cases} \qquad colour\ u^b = \begin{cases} red = s \cdot u^a \\ green = 0 \\ blue = u^b \end{cases} \tag{3}$$

As shown in fig. 5, eq. 3 makes the LEDs glow in red for user u^a and in blue for user u^b based on their heart rate (i.e., for each user the LEDs pulse at the same pace of his/her own heart). However, the colours can blend into a magenta hue as the synchronisation value s increases.

4 RELIABILITY TEST

To verify the reliability of the device, we ran a brief pilot test of 4 minutes involving two people. In the first half, *Lokahi* was used

[7]This could happen in the previous version of the device, where the chip memory limitations allowed to work on a window of only 2 seconds.

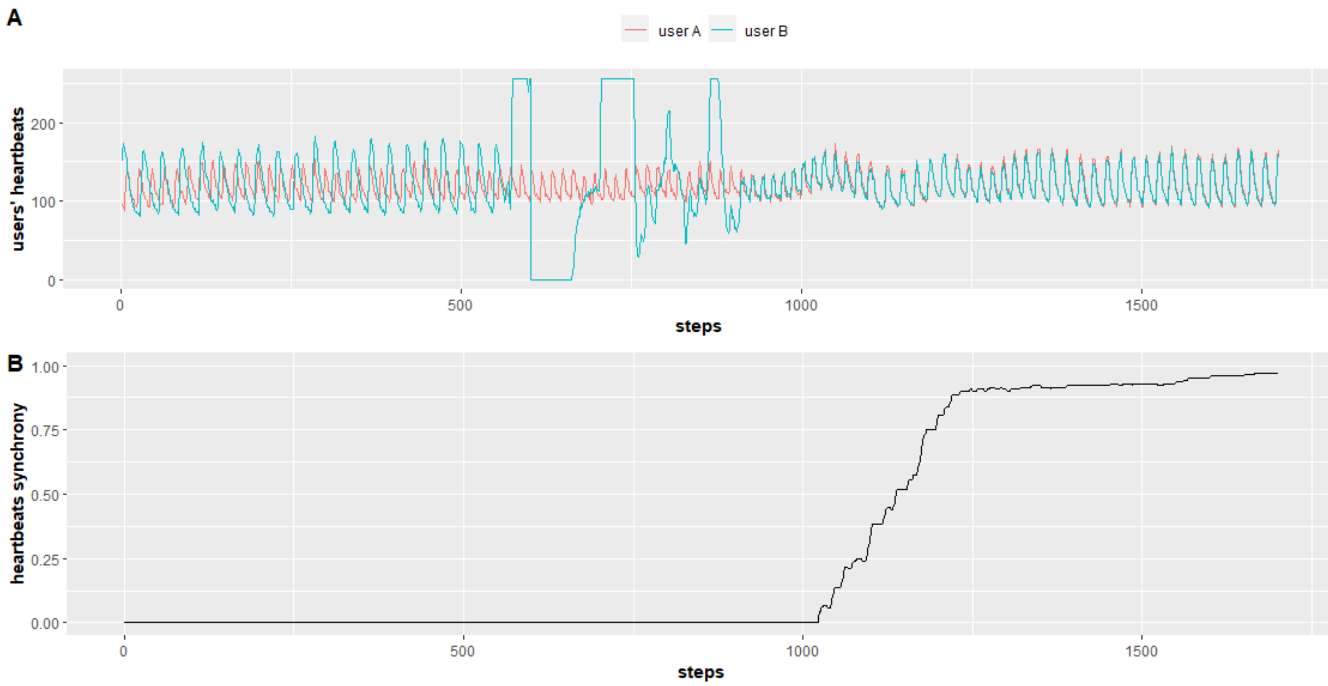

Figure 6: The figure shows a subsection of the data saved in the pilot test, namely the central part of the test. In this segment, lasting around 56 seconds (1700 steps) three sections can be observed. Steps 0-500: graph A shows the heartbeats of the two users; as there is no sync, graph B shows a flat line; step 500-1000: one user wears both sensors, so some noise is detected in one of the two sensors until the signal stabilises; step 1000- 1700: one user plays the role of both partners; in this case, the line in graph B starts to increase and reaches the maximum in around 10 seconds.

with both participants. In the second half, only one participant used the device, wearing both PPG sensors. This segmentation was used to test the capability of the device to correctly detect a 'forced' synchronisation[8].

The results are shown in fig. 6: in graph A, the red and blue lines indicate the PPG signals of the two sensors. In graph B, the black line indicates the synchronisation level of the two signals (i.e. the value s in eq. 2). As shown, in the first half of the graph, the sync value is close to 0 as the two signals are not synchronised (the partners see their heartbeats visualised with their colour, blue or red). In the second half of the graph, one user wears both sensors to mimic two highly synchronised partners. As shown, the sync value increased within around 9.9 seconds, making all the LEDs colours blend into a unique magenta hue.

5 FUTURE WORKS AND CONSIDERATIONS

The current work confirms that *Lokahi* is a reliable device ready to be used in pilot studies. The next steps will then concern three different directions of research:

- *Experimental testing*. We plan to run a pilot experiment involving several couples of partners. The participants will be required to hug each, for about 8 minutes, and to focus on *Lokahi* pulsing lights. This will enable us to collect data and to observe the users' capability to synchronise their heartbeats, using the device's visual feedback. Importantly, this test will allow the evaluation of the partners' associated feelings of connectedness and intimacy.
- *Device hardware improvement.* In a new prototype, currently under development, we are adding additional sensors for the detection of users' breathing and connecting them to actuators such as vibrating motor discs.We chose haptic feedback as an output for breathing to augment the intimacy with an on-body sensation. Once vibration-based haptic actuators and breath sensors are applied, it would be interesting to compare the cardio-visual and respiratory-haptic features of the device to understand the relation between interoceptive and exteroceptive signals. Indeed, we imagine that these new inputs and outputs could enrich the sensory feedback for the partners, possibly augmenting the feeling of closeness and intimacy.
- *Functional wireless improvement.* In the new prototype we implemented a new interesting software feature that allows two distinct devices to connect to each other through a local, ultra-high capacity, wireless network[9]. A pilot test, where two users were located in two adjacent rooms of our laboratory showed how the devices can exchange the heartbeats

[8]The video of this test is available at the link https://drive.google.com/file/d/1Ht0ILrCrbxuGtRyIWLAgtjfpoIYFCW82/view?usp=share_link

[9]We used the national GARR network, available for research institutes: www.garr.it/en/infrastructures/network-infrastructure/our-network

signals with a 20 Hz frequency. This is enough to provide real-time feedback to the users. In the not-too-distant future, when internet communication will have a higher communication rate, two physically distant partners could use *Lokahi* to feel close and share feelings. This use could be relevant in extremely stressful situations where two people in a relationship are forced to stay far from each other, for example during long-lasting space missions [5, 6].

The above-mentioned proposals will try to address 4 Research Questions (RQ) but are not limited to:

- RQ1: does the visual heartbeat – and soon, the haptic-breath – feedback promotes a genuine feeling of the intimate connection between partners?
- RQ2: to what extent the two users can synchronise their signals, thanks to the visual and haptic feedback?
- RQ3: to what extent does the potential synchronisation augment the feeling of connection?
- RQ4: what kind of feeling can be experienced with the use of *Lokahi* device? Does it elicit in the users only positive emotions? Or also other feelings can be experienced?

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