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An Adaptive Model to Support Biofeedback in AmI Environments: A Case Study in Breathing Training for Autism

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Abstract Biofeedback systems have shown promising clinical results in regulating the autonomic nervous system (ANS) of individuals. However, they typically offer a "one-size-fits-all" solution in which the personalization of the stimuli to the needs and capabilities of its users has been largely neglected. Personalization is paramount in vulnerable populations like children with autism given their sensory diversity. Ambient intelligence (AmI) environments enable creating effective adaptive mechanisms in biofeedback to adjust the stimuli to each user's performance. Yet, biofeedback models with adaptive mechanisms are scarce in the AmI literature. In this paper, we propose an adaptive model to support biofeedback that takes the user's physiological data, user's adherence to therapy, and environmental data to personalize its parameters and stimuli. Based on the proposed model, we present EtherealBreathing, a biofeedback system designed to help children with autism practice box breathing. We used the data from 20 children with autism using EtheralBreating without adaptation mechanisms to feed an adaptive model that automatically adapts the visual and audible stimuli of EtherealBreathing according to changes in each user's physiological data. We present two scenarios showing how EtherealBreathing is capable of personalizing the stimuli, difficulty level, or supporting the therapist decisions. Results are promising in terms of performance and personalization of each user model, showing the importance of personalization for AmI technology. Finally, we discuss challenges and opportunities in using adaptive models to support biofeedback in AmI environments.

Keywords Biofeedback · adaptive · autism · AmI enviroments

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1 Introduction

Ambient intelligence (AmI) technology refers to ubiquitous and pervasive environments that are sensitive and responsive to the presence of people [14]. An AmI technology can be aware of the state of the user's environment using sensors and inferences, can make decisions about the data collected using a variety of techniques, and can also affect the environment using actuators. A particularly promising application for AmI technology is in health monitoring and biofeedback [5].

Biofeedback is a process that can be used for training individuals to recognize and modify their body's physiological signals (e.g., heart rate, galvanic skin response, breathing) for improving their health [41, 48, 57]. Biofeedback systems have shown positive results for regulating physiological signals in more than 100 clinical conditions such as reducing headaches, stress, asthma challenges, and so forth [3].

Currently, there are biofeedback models created for specific scenarios in healthcare [3, 11, 26] and biofeedback systems developed following those models [2, 52]. However, some of the main drawbacks of these models is that they do not take into account the capabilities of the end user and do not enable personalization. Biofeedback models heavily rely on a human operator (i.e., therapist) for the personalization to each user's needs, profile and capabilities (e.g., variations in the autonomic nervous system, medical conditions or stimulus preferences). Biofeedback personalization can be divided into two ways: a) default personalization, that is, the same stimuli and parameters obtained from a general view of all its potential users; and b) manually controlled by a specialist in a dedicated environment. This personalization makes Biofeedback systems expensive or difficult to use, often making them inaccessible or not particularly efficient since a "one-size-fits-all" solution will not appropriately serve everybody's needs.

Regardless of current biofeedback challenges to make such training available "everywhere and at any time", biofeedback systems have been particularly promising in supporting the needs of autism showing promising clinical results in the regulation of their autonomic nervous system (ANS) [50, 17]. According to the DSM-V [7], autism is a spectrum disorder characterized by "persistent impairment in reciprocal social communication and social interaction, and restricted, repetitive patterns of behavior, interest, or activities. These symptoms are present from early childhood and limit or impair everyday functioning". Children with autism require personalized feedback when using biofeedback systems to account for their sensory diversity [22, 28, 29]. This diversity in sensory modulation may present a mismatch in their internal characteristics (e.g., attention, emotion, sensory processing) [29].

Children with autism exhibit differences in the ANS including atypicalities in the amygdala [37, 45, 46], anterior cingulate cortex [38] and insula [6, 15]. These brain structures play a key role in modulating the ANS response. Therefore, it is not surprising that several studies have reported atypical signals at the peripheral nervous system level, specifically related to a dysautonomia of the ANS [12]. ANS dysautonomia includes increased heart rate [8, 24, 33], decreased initial vagal tone [33], and increased breathing rate [20, 21, 49]. In addition, children with autism experience emotional variations and problems with self-regulation of their emotions. These challenging behaviors may be exhibited in the form of aggression, disobedience, or self-injury. Challenging behaviors are common in children with autism [30] which, without appropriate intervention, may persist over the long term and put their educational and social opportunities at risk. Children with autism may exhibit symptoms of anxiety, stress, and depression during challenging behavior. During a period of stress or anxiety, the mechanisms responsible for increased heart rate and blood pressure are not fully understood. However, it is known that sympathetic activation -i.e. activation of the system that controls much of the human body in situations of danger, stress and/or fear- leads to increased release of catecholamines during these periods. This sympathetic activation is later reflected in an increase in heart rate [30]. Some strategies used to lower heart rate include the practice of breathing exercises [53, 23]. and biofeedback systems. Several studies have reported a decrease in heart rate using breathing techniques in children.

Studying adapting models to support Biofeedback in AmI environments would allow the development of biofeedback systems that personalize the stimuli and training according to the needs of children with autism. We hypothesize that biofeedback models using adaptive mechanisms can be key to the success of developing biofeedback systems in AmI environments in support of the needs of children with Autism, and to a certain extent in other healthcare scenarios.

In this paper, we present an adaptive model for Biofeedback in AmI environments that takes into account users' physiological variables, users' adherence to therapy, and other environmental variables affecting users' physiological data. Through this adaptive biofeedback model, several implementations can be derived to personalize biofeedback training. To illustrate how the model can be used in practice, we present EtherealBreathing, a biofeedback system designed to help children with autism practice breathing exercises. The adaptation of EtherealBreathing is achieved by inferring the next level difficulty of the breathing exercise, as well as the type of stimuli provided to the children. This is achieved by taking the user's physiological data and their adherence to the therapy as an input to a fuzzy logic system that selects the proper difficulty level and stimuli as an output. We present two scenarios showing how EtherealBreathing is capable of personalizing the stimuli, difficulty level, or supporting the therapist decisions

The contributions of this work are:

- An adaptive model to support biofeedback in AmI environments.
- A biofeedback system implementing the adaptive model to support box breathing in children with autism.

2 Related Work

The literature in Biofeedback can be divided in clinical biofeedback and ubiquitous biofeedback [3]. Clinical biofeedback is performed under the supervision of a health care specialist, usually in a clinical setting or a space dedicated to biofeedback therapies. The specialist follows a procedure to provide biofeedback to the user [21]. Ubiquitous biofeedback, on the other hand, focuses on the user's personal environment. This biofeedback is not limited by time or the clinical environment. Ubiquitous biofeedback systems usually instrument the environment to sense the user's physiological data and return visual and auditory feedback peripherally, among other things, to avoid a burden on the user's cognition [57], to treat negative moods such as sadness and anxiety [49], or improving balance [16].

Usually, the development of those systems, either clinical or ubiquitous, follows a traditional model consisting in Body, Biofeedback, and Mind as a closed loop [3]. Although other biofeedback models can be found in the literature, in this work we discuss only those focused on the creation of biofeedback systems in AmI environments.

For this, we conducted a literature search of the proposed models in AmI biofeedback. We reviewed the objective of the model, and the components it contained. For example, Liu, Hu and Rauterberg [26] described a software architecture as a model to create an in-flight music biofeedback system to promote stress-free air travel. Passengers' signals are acquired through non-intrusive sensors. These signals are modeled to determine if the passenger is in a stressed state. If so, the biofeedback system recommends a music playlist to reduce the passenger's stress. Bodolai et al. [9] present a framework that provides a solution for monitoring students learning with mobile applications. This framework uses biofeedback to allow the teacher to infer the students' state of mind to sustain their learning process. Similarly, Ahn et al. [1] propose a framework that allows the continuous monitoring and control of the biofeedback system devices. The modularized hardware architecture allows monitoring of daily life activities and providing automated intentions. They implement a prototype to validate the framework. Finally, Al Osman et al. [4] presents a reference model of a ubiquitous biofeedback system that is divided into two processes: the Awareness Process, and the Assistive Process. The awareness process allows the user to be aware of their physiological data, while the assistive process gives the user feedback that allows the user to modify their physiological data.

Under the same direction, we did a search for biofeedback systems at AmI. The information gathered in this work was: a) Biofeedback system objective, b) components used (sensors, pre-processing, stimuli), c) results. The table with the revised works can be found in Appendix 1.
To mention some works that would have benefited from an adaptation mechanism we can mention the work of Swanson [51] presents a study whose objective was to determine whether a 6-week course of heart rate variability (HRV) biofeedback and breath retraining could increase exercise tolerance in 29 participants. In [51], they note that a combination of HRV biofeedback and breath retraining may improve exercise tolerance, plus cardiorespiratory biofeedback has the potential to improve cardiac mortality and morbidity in heart failure patients. However, there are characteristics of the participant that were not taken into account (shorter or taller height, older age, higher body weight, gender, pulmonary disease, cardiovascular disease).
Another work is that of McLean [31], in which they present a device called Moodwings. Moodwings is a wearable butterfly that mirrors a user's real-time stress state through actuated wing motion. The purpose of MoodWings to function both as an early-stress-warning system as well as a physical interface through which users could manipulate their affective state. The aim of moodwings was to present the state of stress in the form of a tactile stimulus. The participants reported "not feeling control over the butterfly", thus creating an effect contrary to the desired one. An adaptation during the course of the study would have detected an increase in the participant's physiological signals, making the decision to decrease

the movement of the butterfly's wings.

To the best of our knowledge, no biofeedback model or system has been defined taking into account parameters such as: physiological user data (profile), user's adherence to therapies, and environmental variables to provide personalized stimuli. Such data should be considered to meet the demands of healthcare scenarios. For example, models should consider the users' physiological data to determine the states of an individual's ANS such as: stress, anxiety or dysautonomia. Environmental variables can help us to understand changes in users' ANS and provide the appropriate feedback to the user. Also, if the system is aware of how users are adhering to the training, the system can make decisions based on their performance.

3 A model for adaptive biofeedback systems

In this section, we present a model that can guide the construction of biofeedback systems taking into consideration physiological user data, user adherence data, environmental data. We first describe the overall model, and then describe each of the modules of the model, their rationale, and how they relate to each other.

3.1 Adaptive model

The *(Body-Biofeedback-Mind)* loop begins when the User's body physiological data, User's adherence to therapy and Environment data are measured by the *Sensors* (Figure 1). The Sensors module captures the data and send them to the *Pre-processing* module. The *Pre-processing* module receives, filters, and processes the data by extracting the most relevant features. These features are then sent to the *Personalization* module. The *Personalization* module adjusts the parameters and stimuli in relation to the user preferences and performance. It also prepares and sends the data to the interface showing the *Stimuli* to the user as an output. User data is stored in a *Historical register*. Finally, the *Stimuli* module presents this information to the user. In this way the loop begins again. Additionally, a *Therapist* can support the biofeedback session by manually readjusting stimuli, updating patients' performance, or ending the session when required.

The adaptive model is a closed loop i.e., the signals coming from the user body allows the selection of the stimuli. These stimuli aim at producing a change in the user's mind, and thus in the signals coming from the user body. With the proposed model, the biofeedback system can change (1) the sensory stimulus according to the user preferences, (2) the feedback parameters (i.e., stimulus intensity, exercise limits, engagement mechanics) according to the user performance, (3) the system can modify the feedback parameters to maintain engagement or the system can change the stimulus if the stimulus that is being presented collides with a stimulus from the environment.

We next describe each of the modules found in Fig. 1.

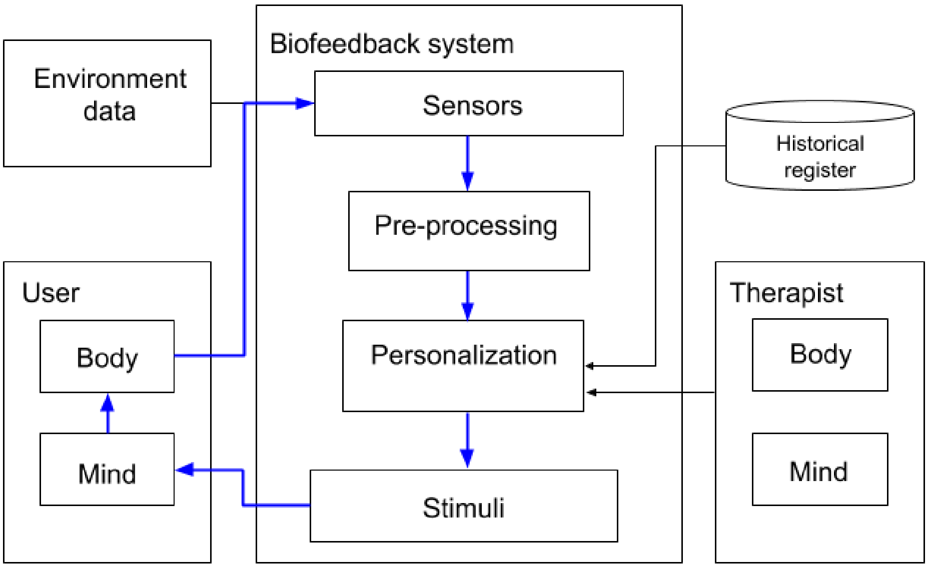

Fig. 1 A model proposed for adaptive Biofeedback. Body-Biofeedback-Mind cycle (blue lines)

3.1.1 User: Body - Mind

Usually, the user is interpreted as the body-mind conjunction [3]. The mind is the set of cognitive abilities that encompasses processes such as perception, reasoning, consciousness, memory, among others. On the other hand, the body is the physical part of the user. In our model, *Body* (see Figure 1) refers specifically to physiological signals of the body. In this way, a closed-loop is formed, capturing the body's physiological signals, processing them in the biofeedback system, and sending them back to the mind for a change in mental-emotional state. *"Every change in the physiological state is accompanied by an appropriate change in the mental-emotional state, conscious or unconscious, and conversely, every change in the mental-emotional state, conscious or unconscious, is accompanied by an appropriate change in the physiological state"[18].*
We take in consideration two user variables, user's physiological data and user's adherence to therapy:

User's physiological data is all the data pertaining to the ANS (e.g., breathing rate, heart rate, heart rate variability, galvanic skin response, balance). These user's physiological data can help the adaptive system to make decisions about which thresholds to set. For example, if the biofeedback system seeks a reduction of stress taking into consideration the heart rate and galvanic skin response, the system should measure the current state of the patient (stress state) and decide what thresholds it should offer the user to achieve a neutral state (usually presented as a baseline in sensing devices). In addition, the physical characteristics of the user should modify these data (i.e., age, weight, height, gender). The set of these signals together with these characteristics, will allow to adapt and create the user's profile.

User's adherence to therapy can be understood as the follow-up of the user to the biofeedback session. Adherence to therapy provides relevant information about the effectiveness of the biofeedback session on the user. This can help make decisions such as changing or adjusting parameters of the biofeedback system, customizing the stimuli, or stopping the biofeedback session if necessary.

3.1.2 Environment data

The adaptive biofeedback model takes into consideration all environmental data that can have an impact on both the user and the biofeedback system (e.g., ambient temperature [56], lights [36], or sounds [54]), depending on the relevance to the task being carried out. For instance, a room temperature increase could cause an activation in the user's sympathetic system. On the other hand, ambient light may affect the visibility of the biofeedback system (if visual stimuli are provided).

The adaptive biofeedback systems must consider these variations in the environment to readjust the parameters and counteract the effect that the environment could have on the user. For this reason, biofeedback systems should take into account the effect of environment variables to adapt the users preferences.

3.1.3 Sensors

The *Sensors* module aims at measuring User and Environmental data.This model considers three types of sensors: (1) user's physiological data sensors, (2) user's adherence to therapy sensors, and (3) environmental sensors.

The *user's physiological sensors* measure physiological data in real time and convert these data into electrical signals that the computer can process [13, 39]. For example, there are sensors that can measure cardiovascular activity through electrocardiography (ECG) or photoplethysmography (PPG), –from which heart rate, heart rate variability, and pulse transit time (PTT) can be derived. Some devices used for these purposes are oximeters and smartwatches.

Adherence sensors measure the degree to which the patient's behavior follows the instructions provided by the biofeedback system. For example, camera-based eye tracking can be used to infer whether the user remains attentive to visual stimuli [43]. Using brain-computer interfaces, we can obtain the alpha, beta and gamma waves to infer the user's level of attention or engagement with a task [27].

Environmental sensors measure changes in the user's environment (e.g., temperature, lights, sounds). For example, we can measure light intensity through photocells or photoresists. The intensity of these changes in the environment, can affect the stimuli provided by the biofeedback system.

3.1.4 Pre-processing

The *Pre-processing* module receives, filters, analyzes, and extracts the most relevant features from the data coming from the *Sensors* module. This Pre-processing can be done in two ways:

a) The sensors send the pre-processed information: currently there are biofeedback devices that already perform this pre-processing. In this case, the quality of the data must be ensured by avoiding any type of noise or unwanted data.

b) Sensors send the raw signal. In this case, the *Pre-processing* module must condition the data and extract the most relevant characteristics. Some examples of algorithms used for conditioning are: amplification, multiplexing, isolation and linearization.

For example, if we want to extract the number of average breaths of a user, we can use a device that gives us directly that data, or we can use a device that gives us the values of accelerometry and extract the inhalations and exhalations of that value.

3.1.5 Personalization

The *Personalization* module adapts the parameters or stimuli of the biofeedback system. The *Personalization* module takes as input the features extracted from the user's physiological data, user's adherence to therapy, environmental data (Fig. 2).

Data will be processed with a *Adaptation* mechanism that will *Measure the effectiveness*. The Adaptation mechanism can be implemented by generated models using the convenience algorithms (this will depend on the type, quantity and form in which the data need to be processed). To *Measure effectiveness,* the intelligent models can establish rules to consider the relation of the user's input values, and *Update the user profile*. For example, add to the profile the preference or dislike of some stimulus, establish the capabilities that the user has to perform the therapy and reduce or increase the parameters. Finally, the *Personalization user manager* module would store this information in the *user's Historical register* and send the processed data to the *Stimuli* module.

3.1.6 Stimuli

The *Stimuli* module should unfold the representation of the personalization module. The *Stimuli* module incorporates the representation of the Personalization module. There are multiple ways to give feedback to the user.

However, the right stimuli to be presented to the participant by the system must be evaluated based on the user's preferences, needs, context, and type of biofeedback. For example, some studies show that children with autism have variations in stimuli (this may differ between individuals) [44]. Other studies have evaluated visual [58] or auditory [19, 35] stimuli integrated into the environment to provide parallel biofeedback. The aim is not to generate an extra cognitive load to the activities performed by the user.

3.1.7 Historical register

The use of biofeedback systems is done for continuous periods, such as hours, days, weeks, or even months [3]. For this reason, the biofeedback system must include a historical record that stores the user's profile. The *Historical Register* stores the user profile as it progresses through the biofeedback sessions, this module enables a) knowing the initial parameters with which the system must start, b) analyzing the user's performance to know if the session has a long-term effect, c) updating the user data if required by the therapist.

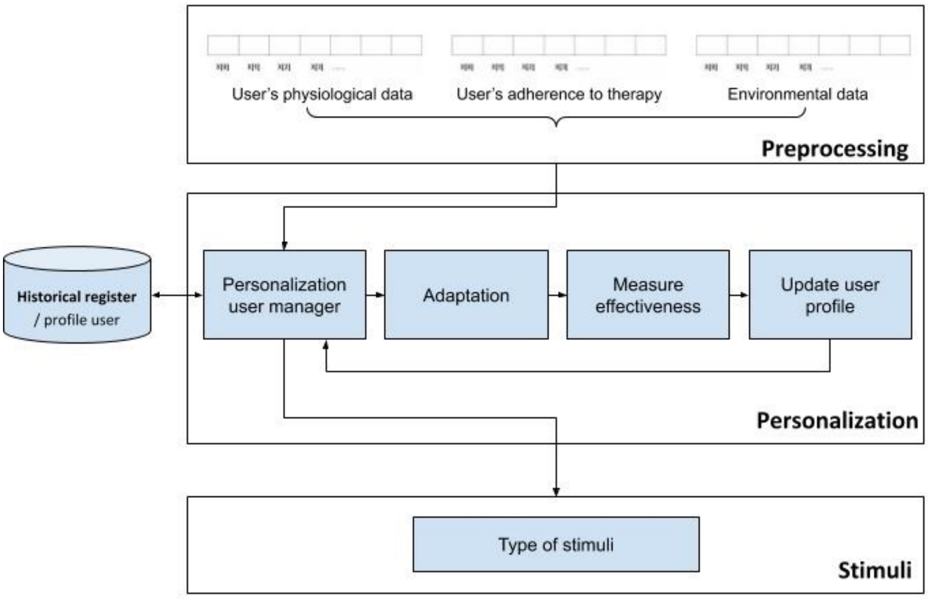

Fig. 2 Proposal for the readjustment of parameters and stimuli. The most relevant features are sent as a vector from the Pre-processing module to the Personalization module, which then adjusts the parameters and stimuli and sends them to the Stimuli module.

In addition, the Historical Register can also include initial parameters that the user or therapist can modify. These parameters can be the preference of sensory stimuli, medical conditions, and daily stress schedule.

3.1.8 Therapist

In order to provide external assistance, the biofeedback system extends the awareness model by proposing an assistive component: a *Therapist*. The *Therapist* is a health specialist who can assist the user's biofeedback process, serving as a guide if necessary. The *Therapist* may perform the following actions: Establish the main parameters of the biofeedback system, follow up with the user's doctor, modify the parameters depending on the progress of the user or stop the biofeedback sessions if necessary.

4 Case study: EtherealBreathing, a biofeedback system to support children with autism in box breathing practice

To illustrate how the adaptive model can be instantiated by a biofeedback system, we present the development of EtherealBreathing, which is a bio-feedback holographic game to support children with autism with the practice of box breathing exercises.

4.1 EtherealBreathing prototype

We used an iterative design process for prototyping EtherealBreathing. EtherealBreathing is a pyramidal prism of acrylic placed on a wooden base of 19 cm height, 28 cm width, and 21 cm depth (Fig. 4). EtherealBreathing has an adventure-type story, which consists of helping a guiding guru called "Akhi" regain the balance of the elements to save the world. Children have to practice box breathing exercises to collect the elements that are unbalanced in each temple. Game dynamics are as follows:

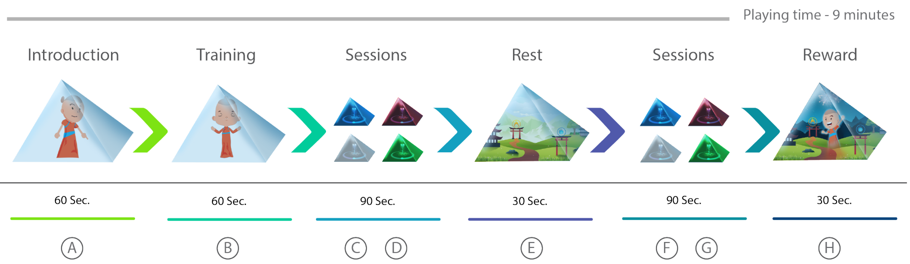

Fig. 3 Dynamics of EtherealBreathing:the child has to achieve balance in the world through a series of blocks. Once balance is achieved in the sessions (C,D,F,G), the world regains its balance.

- a) Akhi tells the child that the world has lost its balance. The child must achieve balance in the 4 breathing sessions.
- b) Akhi shows the child how to do the breathing, first inhaling and then exhaling.
- c) Blocks c,d,f,g are the main sessions. The child has to do box breathing to achieve the balance of the element. The element is selected by the system depending on the number of breaths taken and the number of prompts needed. For the first level, the system uses the number of breaths from the training. In total, the child takes 4 sessions of breaths.
- e) Akhi reinforces the child with verbal and visual support. This module also serves as a rest and to prevent the child from having any adverse effects (dizziness) during the session.
- h) Finally, Akhi tells the child that she has achieved mastery of the elements. Visual and auditory elements are displayed to the child's satisfaction.

4.2 EtherealBreathing Biofeedback loop

The cycle begins when the user's breathing (i.e., *User's physiological data*) and visual attention (i.e., *adherence to therapy*) are measured (Fig. 4.a). Breathing is measured by a chest sensor and visual attention is measured by a camera (Fig. 4.b). The *Sensors* module sends the information to a tablet which extracts the number of breaths and visual attention time per level (*Pre-processing* module, Fig. 4.c). The *Pre-processing* module sends this information to the *Personalization* module. The *Personalization* module determines a) the difficulty of the next level

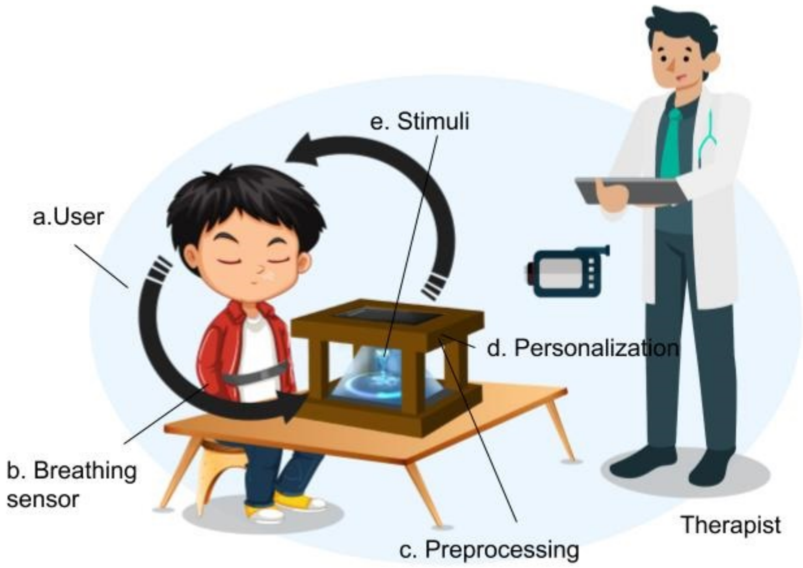

Fig. 4 EtherealBreathing's adaptive Biofeedback cycle

based on the breathing-prompts relationship (for more details see section 4.2.7), b) the type of stimulus based on the visual attention-breathing relationship (Fig. 4.d). This personalization is achieved from a series of established rules developed with fuzzy logic. Finally, the *Personalization* module sends the information to the *Stimuli* module. The *Stimuli* module displays the information (visual - auditory) on the tablet screen which is reflected in the holographic interface (Fig. 4.e). This information returns to the user and the cycle begins again. This response can be presented as an activation in the parasympathetic branch, generating a feeling of relaxation in the body. This is when the cycle begins again (Body-Biofeedback-Mind) [18]. Additionally, a *Therapist* follows up on the session.

4.2.1 EtherealBreathing User

EtherealBreathing is designed to help children with autism practice box breathing. We take into account the physiological data of children with autism and their preferences to maintain their engagement during the therapy and to properly personalize biofeedback system.

For EtherealBreathing, we use the breathing of children with autism as the physiological variable of interest. We define breathing ranges following a clinical model according to the age of the child (Appendix 2). These ranges indicate the proper number of breaths children may practice without demanding from them to hold their breath until becoming a potential risk to their health (i.e., hyperventilation and hypoventilation). It should be noted that longer breathings within the range are more difficult to conduct than regular breathings. However, they are more recommended to support relaxation in children with autism. Therefore, EtherealBreathing increases or decreases the difficulty level of each exercise based on the duration and the number of breathings to be completed on each trial (see section 4.2.7).

For simplicity, as an adherence mechanism, consider the amount of time of each child's visual attention during the therapy as our variable of interest. Visual attention will help us infer whether a visual or auditory stimuli may result in cognitive overload.

4.2.2 EtherealBreathing Environment

EtherealBreathing should be installed in a room taking into account the lighting and potential environmental noise. The lighting of the room is important to correctly display the visual stimuli that the tablet reflected on the hologram. Finally, the background audio is important to allow children to correctly listen to the character's narrative, and auditory prompts given by EtherealBreathing.

4.2.3 EtherealBreathing Sensors

EtherealBreathing uses two sensors to monitor users' breathing and visual attention. To sense the breathing, EtherealBreathing uses a smartwatch (Asus Zenwatch with Android Wear operating system and Qualcomm Snapdragon 400 processor) embedded in an elastic band. The smartwatch is placed on the user's chest (at the level of the diaphragm, just below the lungs) to measure their stomach expansion (inhalations) and contraction (exhalations). The smartwatch extracts accelerometry raw data and then sends them to the tablet via Bluetooth. Currently, there are multiple breathing sensors on the market [55, 25, 42], after an evaluation of cost, usability, data acquisition, we decided to implement a breathing sensor with a smartwatch watch. To test the precision of the sensor, we use the data of 5 young adults (average age = 23.2, sd= 1.3). We placed the users in a dedicated space for the test. After this, we proceeded to the calibration. Calibration consisted of detecting the maximum expansion and minimum contraction values that the user can make. These values are taken as initial values for the therapy. Sensor data were compared with a videorecording (ground truth) of the session. Table 1 presents the confusion matrix.

		Exhalation	Non-Exhalation	
Actual	Exhalation	23	3	26
	Non-Exhalation	1	24	25
		24	27	

Table 1 True positives (TP)/ True negatives (TN) / False positives (FP) / False negatives (FN) of breathing by P3, which yields Precision=88.8% and Recall=95.0%

From the sensor data, 23 real exhalations (true positives), 3 non-real exhalations (false positives) due to noise on the sensor, 1 undetected exhalation (false negative) and 24 correctly labeled inhalations (false positives) were detected. With these data the precision and recall were calculated. Below are the accuracy and recall data for all participants (See Table 2).

Participant	Recall	Precision
P1	1.00	0.96
P2	0.96	0.96
P3	0.95	0.884
P4	0.958	0.958
P5	0.923	0.96
Avg	**0.95**	**0.94**

Table 2 Precision and Recall of P1 to P5 during the 4-minute pilot

On average the precision of the sensor is 0.95 (sd= 0.027). The precision of the sensor is good due to the controlled conditions of the pilot test where the data was collected, as well as the age of the participants.

On the other hand, to sense the visual attention we use an RGB camera (Sony CX405). The camera was placed 50 centimeters away from the child. The height of the camera was set taking into account the child's height. Visual attention is inferred from the time the child has her eyesight on the hologram.

EtherealBreathing has a light sensor integrated into the tablet. The sensor collects information from the ambient light and automatically adjusts the screen brightness of the device. In addition, EtherealBreathing has a microphone which is used to adjust the volume level. These adjustments are made to provide a better user experience.

4.2.4 EtherealBreathing Pre-processing

EtherealBreathing uses a plug-in to perform the communication between the smartwatch and the tablet. This plug-in is installed on both sides, on the smartwatch as a sender, and on the tablet as a receiver. The plug-in is developed for Android and incorporated into an EtherealBreathing *Pre-processing* module. The communication standard protocol used is Bluetooth.

The *Pre-processing* module receives the data from the *Sensors* module. Accelerometry data were filtered to extract the breath through the raw signal. A Butterworth low-pass filter was applied to remove high frequency points. For signal *Pre-processing*, we use the configuration from [47].

Inhalations were calculated by counting the number of peaks per minute. The peaks were detected by the "findpeaks" function, using thresholds for peak distance and prominence based on the signal's features (Fig. 5). We performed the process in reverse to measure the exhalations. The number of complete breaths (one inhalation, one exhalation), is inferred from the distance between two exhalations. Finally the number of breaths, the number of prompts, and the visual attention time is sent to the *Personalization* module.

To analyze the visual attention, we used techniques inspired by structured observation [34]. We focused on the time the child kept her sight on EtherealBreathing. The people who carried out this work were two master's degree students in computer science, with knowledge in human-computer interaction, mobile and ubiquitous computing. The students were trained (40 min) to understand and use the coding scheme and the Boris program. The coding scheme is presented in Appendix 3. The Inter-Observer Agreement (IOA) among the computer science

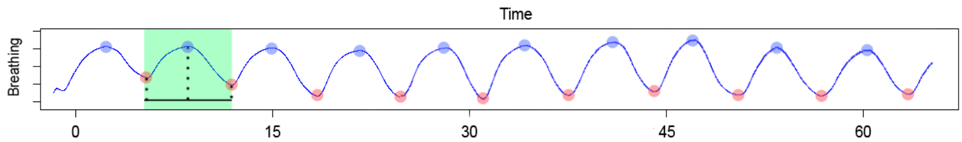

Fig. 5 Log of breathing per 60 seconds of P9 (Blue dots: inhalations, Red dots: exhalations, Green box: distance between two exhalations = one breath)

students was good (kappa = 0.826). The result of this process is visual attention time at each level of EtherealBreathing.

4.2.5 EtherealBreathing Personalization

The *Personalization* module takes as input: the number of breaths, the number of prompts (see section 4.2.7) and the attention time. Ethereal breathing considers two types of personalization: a) Personalization of difficulty: At the beginning of EtherealBreathing, the therapist calibrates the breathing sensor. The therapist places the smartwatch on the child's stomach, and for one minute the child's breath is captured to detect the minimum and maximum level of chest expansion (lung capacity). The maximum and minimum values are used to infer the inhalations and exhalations respectively during the game. Then, EtherealBreathing identifies how the child performed during one level of play (relation: prompts- breathing) to determine the difficulty of the next level. b) Stimulus selection: EtherealBreathing identifies user's adherence (relation: visual attention - breathing) to determine the stimulus to be presented. This stimulus can be auditory, visual, or both. This was done as a first approach to learn children's preferences regarding certain stimuli [8, 22, 28, 29]

EtherealBreathing has 5 difficulty levels (very easy, easy, normal, hard, very hard) according to the number of breaths performed by the children. For the "very easy" level 18 breaths per minute are requested (typical baseline for children aged 6-12 years old); for the "very difficult" level, 10 breaths per minute are requested. A pediatrician determined beforehand the number of breaths (Appendix 2).

To automatically select the difficulty level, EtherealBreathing uses a fuzzy logic system. As many other artificial intelligence techniques, fuzzy logic has been used in video games that seek a simple design in conjunction with intelligent agents [40]. There are multiple works that use fuzzy logic in video games [32, 10]. Due to the linguistic nature of fuzzy logic, the formulation of its rules can be done by experts in the field of fuzzy systems can be used to emulate the reasoning of the expert [32]. Given this premise and taking into account that the rules of EtherealBreathing were built by experts (1 pediatrician, 1 therapist for children with autism), it was decided to use fuzzy logic.

The fuzzy logic system uses two linguistic variables as inputs: prompts and breath. We used an R vector of size 2 with normalized numbers between [0, 1]. Numbers were empirically defined according to the following function: $X = (x1, x2)$ Where $X1$ is the Percentage of prompts needed and $X2$ is the Percentage of breaths.

The *Personalization* module output is a categorical value determined as:

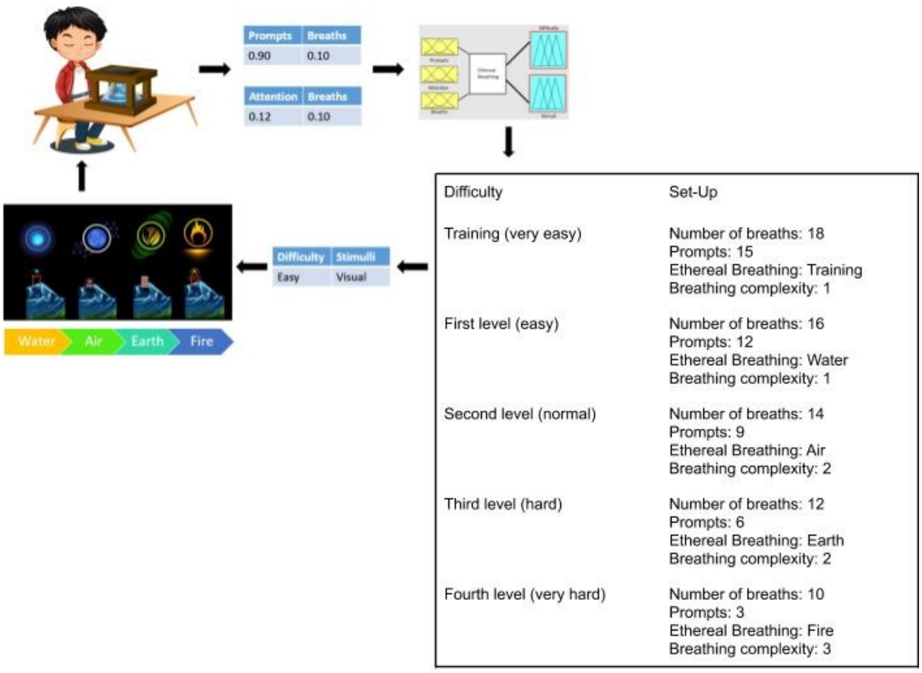

Fig. 6 A mock-up of how the fuzzy system updates the difficulty for the next level.

Y= {Training (very easy), Water (easy), Wind (normal), Earth (difficult), Fire (very difficult)}

For the breaths, we use the values: very good, good, normal, bad, very bad. These values were recommended by a pediatrician (see 4.2.7). For the prompts, we use three members of sets that include: Few, average, many. For the difficulty, we define five sets: Training (very easy), Water (easy), Wind (normal), Earth (difficult), Fire (very difficult). A pediatrician and a one of the authors then defined 22 rules for all possible entries. Algorithm 1 shows an example of three of the rules to increase the difficulty level.

Personalizing the Stimuli of EtherealBreathing

Similar to the previous process *(Difficulty)*, we define the *Stimuli* (relation: attention - breathing) $Z = (z1, z2)$ Where, $z1$ is the Percentage of visual attention and $z2$ is the Percentage of breaths

The module output is a categorical value determined as:

Y= {Good performance, normal performance, bad performance}

Finally, the values of: difficulty level and stimulus, are sent to the output parameter module.

Algorithm 1: Select the difficulty level

Input: Breaths, prompts;
Output: Difficulty level;
If prompts is a *many* **and** breaths is *very bad*;
    then difficulty is *very easy*;
If prompts is *few* **and** breaths is *very good*;
    then difficulty is *very hard*;
If prompts is a *few* **and** breaths is *normal*;
    then difficulty is *normal*;

4.2.6 EtherealBreathing Stimuli

EtherealBreathing provides two types of feedback: visual and auditory. First, visual guidance includes both modeling and real-time feedback on children's breathing patterns. Children have to take the number of breaths required by each temple (the time, number, and duration of breaths are updated according to the difficulty). For example, for the highest difficulty children must complete 10 breathing repetitions with an inhalation and an exhalation lasting 3 seconds each. Akhi shows children how to complete a 3-sec inhalation followed by a 3-sec exhalation. Supplementing the visual modelling, EtherealBreathing uses visual guidance represented in a tridimensional plane for real-time feedback. When a child inhales, a circle plotted on the y-axis starting from a token at 0° moves $+60^\circ$ each second for up to 3 seconds finishing at another token located at 180°. In contrast, when the child exhales the circle moves clockwise 60° each second starting at 180° and finishing at 360° after 3 seconds (Figure 7B). When the child successfully completes both a 3-sec inhalation and a 3-sec exhalation, the element increases 1 point on the z-axis (Figure 7C) for up to 10 points when completing all the repetitions.

On the other hand, auditory feedback includes "elements sounds," according to each temple (i.e., a sound of water, fire, earth, and air), a heartbeat pulse, and a background sound (Figure 8). The "elements sounds" are being played when the child breathes. During an inhalation, the volume of the sound will increase, and during an exhalation it will decrease. The heartbeat pulse with a frequency of 60 beats per minute (BPM) is being played every 3 sec (the time is according to the difficulty), signaling the child how much each inhalation and exhalation must last. The integration of all sounds resembles a sound of water, wind, fire, or air that is heard continuously as background music, and a sound of bells every 3 sec. These sounds complement each other, avoiding an overload of audible stimuli.

4.2.7 EtherealBreathing therapist module

The therapist has two main functions, which are next described:

Set the breathing ranges: The therapist and a pediatrician establish the breathing ranges used in the system (Table 3). These ranges are based on a clinical model used (Appendix 2).

Provide prompts to the child: The therapist provide prompts to the child if deemed necessary (e.g., if the child stops paying visual attention to the hologram, if the child does not do box breathing). These prompts must be spaced at least 4

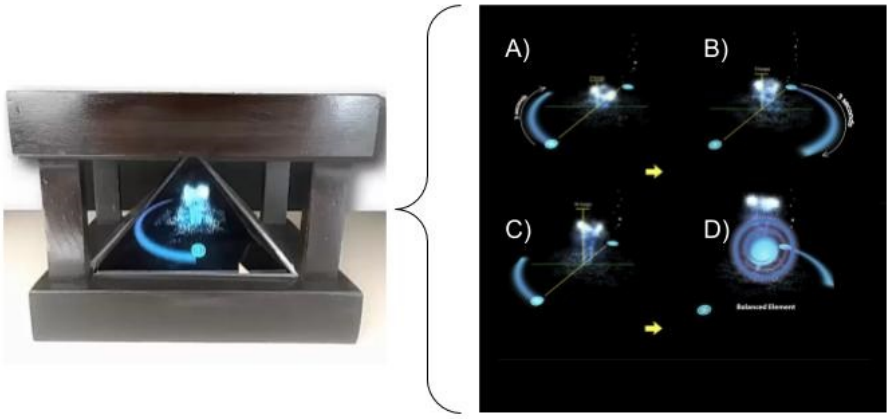

Fig. 7 Water level: A) the child performs the inhalation by turning the left holographic guide; B) The child exhales by turning the right holographic guide; C) When the child takes a full breath, the element rises by one point; D) When the child reaches 10 points, the element is controlled, then a medal appears on the screen.

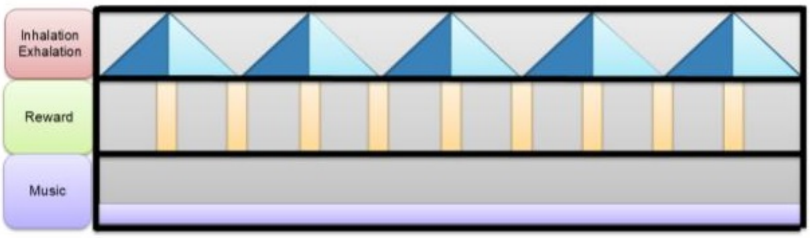

Fig. 8 Sounds in EtherealBreathing(element sound, reward sound, base music)

seconds apart (maximum 15 prompts per minute, 15 prompts per minute = 100% of prompts required).

Additionally, the therapist can stop the therapy if there is a problem. For example, a child may want to leave the room where the session is taking place.

Difficulty	**NBPM**	**Box-breathing (sec)**	**Breaths (%)**
Very easy	18	3	100
Easy	16	3.75	80
Normal	14	4.2	60
Hard	12	5	40
Very hard	10	6	20

Table 3 Breathing rates established by a pediatrician and a therapist. A low percentage of breaths means good performance for the system; NBPM = Number of breaths per minute.

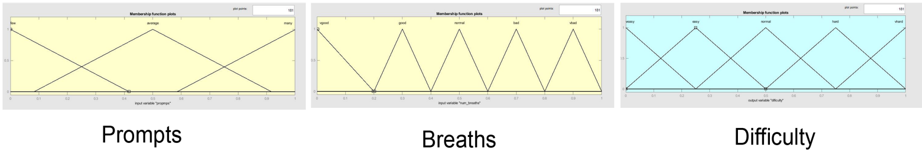

Fig. 9 Fuzzy sets for Input (Prompts, Breaths) and Output (Difficulty level)

4.3 Validation of the Personalization module

To validate the *Personalization* module of EtherealBreathing we conducted an exploratory study where 20 children used EtherealBreathing without the *Personalization* module. Then, we used the children's data during the exercise to validate the *Personalization* module. Finally, to exemplify the use of EtherealBreathing, we present scenarios of two children with autism showing that EtherealBreathing should be able to automatically change its difficulty level and stimuli.

We recruited 20 children from 6 to 12 years old (Mean = 8.3, SD = 1.76) diagnosed with autism of medium and high functioning level (Table. 4), according to the DSM-V [7]. All the children were capable of following the instructions given by Akhi (the game guide). None of the children had respiratory problems nor followed a pharmacological treatment. Participants were recruited from a school-clinic in the Northwest of Mexico. All parents consented to the study on behalf of their children who are minors in Mexico. After that, we conducted the biofeedback sessions.

#	Gender	Age	Functioning level	#	Gender	Age	Functioning level
1	M	7	High	11	M	12	Medium
2	M	6	Medium	12	F	12	Medium
3	M	7	Medium	13	M	11	Medium
4	M	7	Medium	14	M	7	Medium
5	M	8	Medium	15	M	8	Medium
6	M	7	Medium	16	F	7	Medium
7	M	8	Medium	17	F	11	High
8	F	8	High	18	M	9	Medium
9	F	10	Medium	19	M	7	Medium
10	M	7	Medium	20	M	7	High

Table 4 Table of participants with EtherealBreathing

EtherealBreathing was installed in a 3.5m x 4.2m classroom. The environmental variables of the room were controlled so the holographic game could be easily perceived.

We used data from the children who participated in the EtherealBreathing study as input to evaluate if the *Personalization* module is able to personalize the difficulty level and the sensory stimuli according to the performance of each child. For this, we took the number of breaths taken by the children and the number of prompts they required. These data were then converted to percentages.

The percentages were used as input for the Fuzzy System (Figure. 9). Results indicate that the *Personalization* module is able to determine the difficulty for the

Participant	Breaths	Prompts	Output Level
P18	90%	92%	Training (Very easy)
P16	70%	86.6%	Water (Easy)
P2	20%	63.3%	Wind (Normal)
P3	15%	66.%	Wind (Normal)
P14	15%	52%	Wind (Normal)
P5	23%	23.3%	Earth (Hard)
P12	28%	28.8%	Earth (Hard)
P11	37%	37.7%	Earth (Hard)
P8	10%	20%	Fire (Very hard)
P9	10%	14%	Fire (Very hard)

Table 5 Personalization module results (difficulty selection with relation: prompts- breaths)

Participant	Breaths	Prompt	Output Level
P2	20%	80%	Good
P3	15%	93%	Good
P5	23%	80%	Good
P8	10%	75%	Good
P9	10%	90%	Good
P11	37%	33%	Normal
P12	28%	12%	Bad
P14	15%	10%	Bad
P16	70%	85%	Good
P18	60%	55%	Normal

Table 6 Personalization module results; Good, Normal, Bad. Low percentage of breathing means good exercise performance

next level according to the user's performance (Table 5). For example, for P18 who took 90% breaths and needed 92% number of prompts, the *Personalization* module determined that the best EtherealBreathing level for the next session was Training. For the user P9 who took 10% breaths and needed 14 prompts, the *Personalization* module determined that the best EtherealBreathing level for the next session was Fire. These results indicate that for each child, the *Personalization* module is able to determine the most appropriate level based on performance.

Similar to the difficulty, we took as input data the breaths and visual attention from children who participated in the EtherealBreathing study. To modify the EtherealBreathing stimuli, we used the breath and the visual attention paid on the hologram to determine which stimulus to display. The results are shown in Table 6. Performance translated into a change of stimuli, good and normal performance means keeping the current stimulus, whereas bad performance means changing the stimulus.

4.3.1 Scenarios for using the adaptive model

In order to exemplify the importance of personalization, we present two scenarios with real data from our participants.

Scenario 1: Change of difficulty of EtherealBreathing

P8 is a 8-year-old child with high-functioning autism who participated in the sessions with EtherealBreathing. Overall P8's performance was good. In the training phase P8 obtained a percentage of 60% when performing 14 breaths per minute

Fig. 10 P8 using EtherealBreathing the session.

and requiring 50% of the prompts. The*Personalization* module of EtherealBreathing determined that the next exercise for P8 will be the wind level (normal). During that level, P8 decreased the prompts needed to 20% while maintaining the number of breaths, so the *Personalization* module raised the difficulty to the earth level (difficult). During the penultimate temple, P8 obtained a percentage of 10% by taking 12 breaths (close to the desired 10 breaths) and needed 20% of prompts. The *Personalization* module determined that P8 could increase the difficulty (Level of Fire). P8 maintained a good percentage of visual attention to EtherealBreathing during the session, averaging 95% during the 4 temples. For this reason, the system presented visual and auditory stimuli at all times.

Scenario 2: Change of Stimuli

P13 is an 11-year-old child with medium-functioning autism who used EtherealBreathing to learn breathing box exercise. Overall, P13's performance was average. In the P13 training phase she obtained a percentage of 45% of the breaths requiring 30% of prompts. The *Personalization* module determined that the next level for P13 was the wind level (normal). This difficulty was maintained for the second temple as well. For the temple three, P13 improved the breathing rate to 30% and required less prompt 22%, this caused the *Personalization* module to raise the difficulty to ground level (difficult). However, during session 3, P3 kept her eyes off EtherealBreathing almost 90% of the time, yet she was guided by the sounds to continue breathing. Based on breathing and visual attention, the *Personalization* module determined that the best stimulus for P13 was only the auditory stimulus. This behavior was maintained for session 4.

5 Discussions and conclusions

AmI environments that allow the measurement of physiological signals are becoming a reality, as they are more accessible and less intrusive for most of the

Adaptive model	EtherealBreathing
User physiological data	Breathing
User adherence data	Visual attention
Environment	Not required
Sensors	Breathing sensor, Visual attention camera
Pre-processing	Butterworth low-pass filter, Breath count (find peaks)
Personalization module	Fuzzy logic rules (change of difficulty, change of stimulus)
Stimuli	Customized breathing guides (visual and auditory).
Therapist	Personalized difficulty based on the child's performance, personalized stimulation based on the child's preferences

Table 7 EtherealBreathing instantiated in the adaptive model

users. This has been achieved through the development of wearable devices that allow continuous measurement of physiological variables through wireless communication or remotely. Also, the development of technology nowadays enables fast processing and storage of data. These advances in technology have allowed biofeedback systems to become increasingly popular among the population. However, it has not been explored in depth how biofeedback systems can be automatically personalized to the user's needs. Personalization is achieved through a series of variables that modify the behavior of the system, adapting it and adjusting it according to the user's performance. User preferences cannot be assigned in a general way for everyone, hence the need to create dynamic profiles to which the adaptive model can respond. In this work, we proposed a reference model for adaptive biofeedback, which takes into account the user's profile and physiological variables, as well as variables such as adherence and environmental variables to provide adequate user feedback. We also identified a set of practical considerations for the future development of adaptive biofeedback models.

In order to show how the model can be used, we implemented the adaptive model with the development of EtherealBreathing (Table 7), a biofeedback system designed to help children with autism practice. Children with autism often exhibit challenging behaviors that increase their stress and anxiety levels. Biofeedback systems have been shown to be effective in treating stress and anxiety. However, few biofeedback systems are designed for vulnerable populations due to personalization issues. For this reason, EtherealBreathing uses an adaptive mechanism to automatically personalize the difficulty level and the prompts needed according to each child's capabilities and performance. The personalization of parameters on biofeedback systems allows to keep the user interests and engagement throughout the sessions by providing a balance between the difficulty level of the exercise and the user performance, in order to avoid their frustration. The *personalization* module also determines which stimulus is the most suitable for the child based on the percentage of visual attention and the number of breaths. Our future work includes the measurement of extra physiological variables to make the detection of stress states more robust, as well as the measurement of environmental variables to train the adaptive model.

One of the main limitations of this work is the environmental data module since it only takes into consideration the data (environmental data) as input in addition to the sensor used, since currently our sensor is not capable of discriminating all movements of children with autism (rocking, turning, jumping). Future work includes using environmental data to customize biofeedback systems and the development of an appropriate breathing sensor for children with autism. Another limitation is the evaluation of the personalization module. The impact was evaluated with data from children using EtherealBreathing. However, the evaluation of the personalization module could not be carried out.

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