BioFidget: Biofeedback for Respiration Training Using an Augmented Fidget Spinner

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ABSTRACT

This paper presents *BioFidget*, a biofeedback system that integrates physiological sensing and display into a smart fidget spinner for respiration training. We present a simple yet novel hardware design that transforms a fidget spinner into 1) a nonintrusive heart rate variability (HRV) sensor, 2) an electromechanical respiration sensor, and 3) an information display. The combination of these features enables users to engage in respiration training through designed tangible and embodied interactions, without requiring them to wear additional physiological sensors. The results of this empirical user study prove that the respiration training method reduces stress, and the proposed system meets the requirements of sensing validity and engagement with 32 participants in a practical setting.

Author Keywords

Biofeedback; physiological sensing; fidget spinner; stress; respiration training; tangible interaction.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION

People encounter stress in daily life, especially when they are confronted with challenging tasks. When the stress exceeds our coping ability [25], we feel anxious, fearful, and angry. In the long term, the accumulation of these negative stresses leads to the development of serious illnesses [22]. Hence, stress management is an important topic for physical and psychological well-being.

Stress management programs seek to engage the users in ongoing self-regulation; however, the key challenge is that users often drop out of these programs. HCI researchers attempt to build interactive *biofeedback* systems as an intervention solution to address this challenge. These systems provide user-friendly representations of the physiological signals as to increase the users' awareness of their inner states, and help them to adjust their behavior with the adaptive feedback. Providing biofeedback for respiration training is clinically proven to be effective for stress reduction [11][33].

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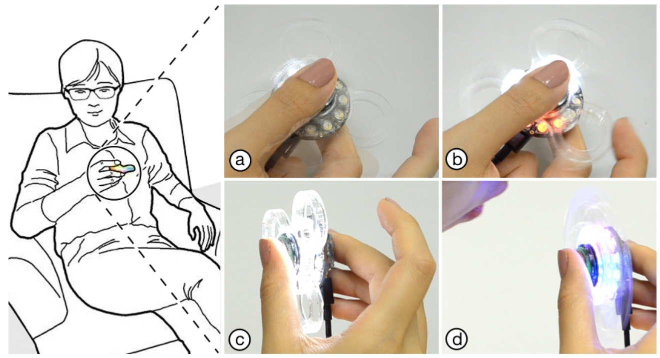

Figure 1. *BioFidget* is a biofeedback system that integrates physiological sensing and an information display into a smart fidget spinner for respiration training. The user (a) activates it with finger flicking, (b) reads his or her stress-related heart rate information from the display, (c) repositions it and switches it to training mode and moves it to his or her mouth, and then (d) blows on it for breathing training by using the adaptive visual feedback tool.

A user who consciously employs this biofeedback technique and paces his or her breathing at around 6 breaths per minute (0.1 Hz) may regulate his or her heart rate at a resonant frequency [18], which maximizes the efficiency of pulmonary gas exchange and relaxes the responses of the autonomic nervous system.

One of the requirements for a biofeedback respiration training system is the utilization of a reliable physiological sensing mechanism. The reaction of a user experiencing stress can be observed from heart rate variability (HRV) [3][31], which can be detected using a pulse sensor with precise timing control; in addition, the way the user regulates his or her breathing pattern for stress reduction can be detected using a respiration sensor. However, the user has to attach these sensors to his or her body before the observation starts. The effort involved in deploying these devices seems to constitute an adoption threshold that should be removed for enabling a useful and casual means of stress management.

We present *BioFidget* (Figure 1), a biofeedback system that integrates physiological sensing and information display into a smart fidget spinner for respiration training. The fidget spinner, invented by Catherine Hettinger in 1993 [13], is a casual finger toy that is designed for stress reduction. A user takes it out of his or her pocket, spins it with little effort, and holds the center pad while it spins. During the rotation, the momentum of the toy provides a pleasant visual-tactile sensory experience. Unlike other conventional eyes-free fidget devices (e.g., fidget cubes, clickers, pens), fidget spinners provide immersive visual feedback, inertial tactile feedback, and adequate form factors that allow for holding still while playing with it. These unique features make the fidget spinner highly advantageous in designing physiological sensing mechanisms and tangible and embodied interactions for casual users.

Figure 1 shows the usage scenario of BioFidget. When the user feels stressed, she takes out a BioFidget from her pocket and spins it to enjoy the visual-tactile experience. After several seconds, she visually observes the change of her heart rate (the white part) and her pulse (the red part) from its display. Then, she re-orients the BioFidget and moves it to her mouth, turning it into a respiration trainer, which guides her to take deep breathes using a rhythmic breathing light. When she exhales, her breath makes the BioFidget spin and provides adaptive visual feedback corresponding to its speed, indicating the quality of her breathing and encouraging the user to play with it again. After 3 minutes of playful and relaxing experience, she puts the BioFidget back in her pocket and returns to work.

Figure 2 and 3a show the basic hardware that we developed to demonstrate the interaction. Each prototype device consists of a photoplethysmograph (PPG) sensor, which has proven to be effective for sensing the HRV values of healthy subjects at rest [8][20], an analog Hall sensor that senses the user's respiration through revolutions of the magnetic wing of the fidget spinner, a visual display for providing physiological information and adaptive feedback for respiration training, and an additional accelerometer for identifying interaction modes (i.e., respiration training or HRV sensing). We further present several alternative designs that utilize various physical forms to optimize these biosensing and biofeedback features; these physical features include a clip to stabilize the PPG sensing (Figure 3b), a fan-shaped wing to increase the sensitivity of the device to respiration (Figure 3c), and a handheld display to enrich the visual expression of biofeedback (Figure 3d). Possible design implications and guidelines for further embodied interaction design are also discussed.

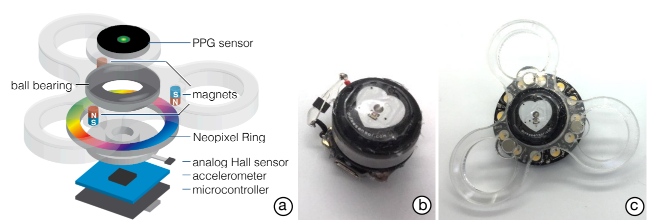

Figure 2. Hardware design of a BioFidget prototype. (a) Overview of components. (b) Center pad that consists of sensing and signal processing units. (c) Assembled state.

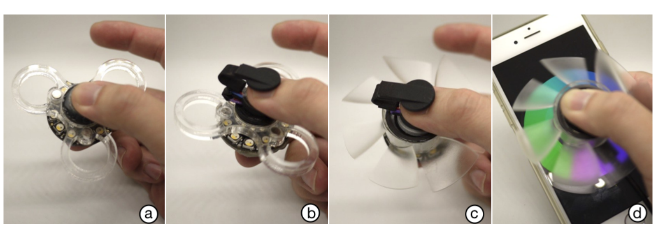

Figure 3. Alternative BioFidget designs. (a) Basic design. (b) BioFidget with an additional clip for PPG sensing stabilization. (c) Fan-shaped wing to react to respiration. (d) BioFidget with a handheld display for rich visual biofeedback.

The evaluation was structured for testing whether the proposed system meets the requirements of sensing validity and engagement with 32 participants in a practical setting. The results show that the proposed biofeedback mechanism effectively supported respiration training and caused positive effects on stress reduction. Regarding sensing validity, the system reliably detects HRV and respiration signals when a user is in a static context. In more casual uses, the system reliably revealed that either the HRV information should be continuously monitored when the user blows on the device or discarded over time when the user flicks the device. In both cases, the physiological sensing remains valid. Regarding engagement, user feedback indicates that BioFidget provides playful and engaging respiration training experiences. The results suggest that the three independent extensions (clip, fan-shaped wing, additional screen) can be applied for further generalizations.

The main contributions of this work are 1) a physical design for a novel smart fidget spinner that both detects stress directly and provides an intervention to reduce stress, which requires no additional physiological sensors to be worn, and 2) user experiences and experimental results regarding this biofeedback system.

RELATED WORK

Tangible User Interfaces for Relaxation

Tangible user interfaces (TUIs) [14] allow users to control and comprehend digital information as it supports direct manipulation and the utilization of spatial knowledge, as well as their cognitive, perceptual-motor, and emotional skills [7]. A user perceives the visual and physical properties of a well-designed physical object; thus, the user perceives affordances [12], interprets the possible utilities according to existing knowledge [27], and adapts to it with minimal learning effort. Nonetheless, a static, physical artifact cannot provide procedural information (e.g., multi-step processes) over time [5], because "an affordance does not change as the needs and goals of the actor change." [23]. To enrich the application space of TUI, the interaction designs often leverage an additional display, which can be on, nearby, or distant from the tangible objects [10]. The display provides contextual feedback and feedforward [37] that users may adapt with time.

Because tangible products afford rich embodied gestures, they can be used to detect the user's mental states. Mind Spheres[1] consist of a pair of LED-augmented wooden spheres designed to enable the users to perform breath regulation with bodily movement and tactile sensation while playing with the spheres. Wensveen *et al.* designed an alarm clock that elicits rich, expressive behavior and demonstrated that the users mood can be precisely analyzed based on how the alarm is set [36]. Fidget Widgets [15] are playful applications running on Sifteo cubes [24] that require mindless hand manipulations to operate. The Relax! Pen [2] senses motion that is associated with stress and provides a calming tactile response. insightfully utilize TUIs for self-regulation [1], which could be a promising approach for designing intervention in stress

[1] http://www.design.philips.com

management. However, obtaining representative physiological signals of stress, such as HRV and respiration patterns, is imperative for improving the precision of stress detection, and may lead to the discovery of more effective stress-reduction interventions than are currently available.

Biofeedback and Respiration Therapy

Biofeedback is a process that enables an individual to be aware of his or her physiological activity. Biofeedback is presented in a user-friendly way, enabling users to increase their awareness of their internal states by comprehending the data presented to them and adapting their behavior based on the data; as a result, the users improve their health and performance [16]. Some biofeedback devices, such as the StressEraser [8] and emWave[2] devices, present physiological information in graphical and numeric forms on a screen. Several previous studies have explored some possible modalities of biofeedback. Yokoyama *et al.* proposed using auditory displays [39] to indicate heart rate data, which would enable users to perceive biofeedback without visual engagement; this would also allow the users to close their eyes during the training. Squid [9] is a smart shirt to deliver haptic biofeedback regarding muscle activities in rehabilitation training. LivingSurface [41] is a shape-changing system that uses surface deformation to provide visual-tactile biofeedback regarding HRV for respiration training.

Respiration training is clinically proven to be effective for stress reduction [33]. Breathing-based biofeedback is helpful as an adjunct to other therapies [11]. Although some conventional smart wearables (e.g., Apple Watch[3]) provides an app for resonant breathing training, an additional respiration sensor is needed to provide further assistance. For example, BreathTray [26] is an ambient desktop widget; this device helps users control their breathing patterns. InnerGarden [28] is an interactive mixed-reality installation that incorporates physiological sensing with immersive biofeedback experiences to promote respiration training. The major limitation of these systems is the on-body instrumentation required for breathing sensing, which limits the availability of sensing and the mobility of the users.

Tangible products can sense heart-rate and respiration data without on-body instrumentation. Practical implementations, such as StressEraser [8], are mono-modal, that is, they only record the heart beat and indirectly present breathing as related to HRV by exploiting the phenomenon of natural variation in heart rate that occurs during a breathing cycle, or respiratory sinus arrhythmia (RSA) [38]. However, these tangible products, in particular those that are evidence-based, such as resonant breathing, tend to be rigid and lack rich interaction [18]. A plausible reason why rich interaction has not been widely adopted by the biofeedback community is that motion artifacts tend to deteriorate the signal quality. In comparison, BioFidget has a built-in motion sensing mechanism, which makes it possible to distinguish and avoid motion artifacts, recording both heart beat and breathing directly and making rich interaction possible.

[2]https://store.heartmath.com/
[3]https://www.apple.com/

DESIGN CONSIDERATIONS

The design of a fidget spinner that can sense physiological information and provide biofeedback must meet two criteria: *technical validity* and *playfulness*. A technology that requires adaptation from the users original ways of playing often also reduces the user's willingness to engage in play. Hence, it is important to seamlessly interweave the technologies with the user's original experience.

Technical Validity

The typical physical form of a fidget spinner consists of two part: the center *pad*, which has two flat sides allowing a user to pinch it, and the *wing*, which is rotationally symmetric, so that it can stay balanced when it is spinning around the center. A ball bearing is used to connect these two parts, keeping the rotation mechanism in a state of low rotational friction. When a physiological sensing method requires physical skin contact, the pad is a favorable location for placing the sensor; when a physiological sensing method requires the reliable connection to be at a higher frequency for sampling (with low levels of noise), a wired connection is efficient for connecting the sensors to the signal processing unit. Therefore, we suggest that both the microcontroller and the sensors be placed on the pad for *technical validity*.

Playfulness

The most basic way of playing with a fidget spinner is to hold its pad with at least one finger, and then spin the wing by exerting a torque, which may be generated by finger flicking or other external mechanical energy sources. The fidget spinner can be between the user's fingertips or on a supporting surface. The wing can either spin clockwise or counterclockwise, according to the direction of torque. Once it is spinning, the fidget spinner stays in balance because the rotation keeps the object's center of mass at the center; the fidget spinner decelerates slowly and steadily due to the small amount of rotation friction. To retain the *playfulness* of a fidget spinner, any additional sensing and display mechanisms should preserve the essential input freedom, rotational balance, and inertial movement in accordance with the user's original experience.

DESIGN AND IMPLEMENTATION

Based on these two design considerations, a BioFidget prototype (Figure 2) was developed for sensing various stress-related physiological signals and gestures from users. All sensor components were integrated into the center pad.

Sensing Heart Rate Variability through a Fidget Spinner

HRV is one of the best predictors of stress [31]. Many conventional wearable devices have the built-in feature of sensing heart rate (HR), which can be calculated as the average beats per minute (BPM). A considerable subset of stress-related research concerns the measurement of Inter Beat Interval (IBI), the time interval between individual beats of the heart, and the use of the information for calculating HRV. IBI values naturally fluctuate from time to time, because the human heart does not beat in a truly steady rhythm. HRV studies track those fluctuations to identify whether a person is stressed. When a person is stressed, the IBI varies, often registering a weak and irregular heart rate; when a person is relaxed, the IBI corresponds to a slow and steady sinusoidal wave.

HRV sensing requires precisely timed voltage sampling. Heart rate information can be measured by using a non-invasive photoplethysmograph (PPG) sensor (Figure 4a) [21]. When a user places a finger on the pulse sensor, the optical sensor receives the light reflected back from the LED during each pulse, resulting in a measurable voltage. Then, the timing of each sample should exact (to the millisecond) for the IBI to be extracted from the Blood Volume Pulse (BVP) waveform. Figure 4b shows an example of a BVP waveform and the features that we used in our implementation of the IBI extraction algorithm, which was mainly based on the one proposed by Smith *et al.* [32]. In our algorithm, a heart beat B is measured at time t when the rising signal crosses an adaptive threshold T_{n-1} defined by the 50% of the previous wave amplitude $A_{n-1} = (D_{n-1} - S_{n-1})$, where D and S refer to diastolic and systolic points, respectively. The IBI between two beats can be calculated as $IBI_n = t(B_{n+1}) - t(B_n)$. To avoid noise and false readings from the d (dicrotic notch), a beat is only detected when the amplitude is large enough (e.g., $\geq 0.01\ V_{ref}$), and $k \times IBI_{mean}$ second after the previous beat, where the IBI_{mean} is maintained using an exponential filter with a smoothing factor α, and the $0 \leq k \leq 1$ is a heuristic value chosen for filtering unwanted vales of d. If no beat is detected during $(2+k) \times IBI_{mean}$ second, the T_{n-1} will be reset to the initial value ($V_{ref}/2$) for deadlock prevention.

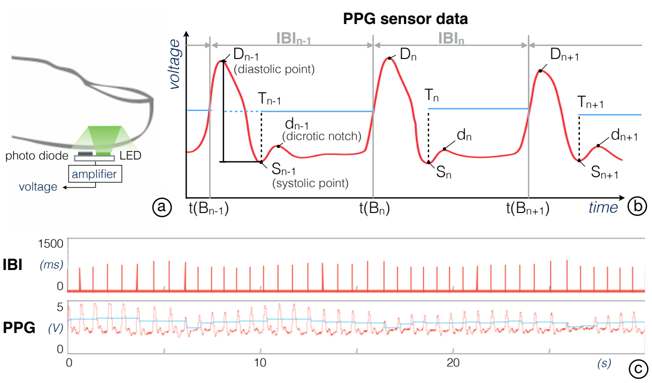

Figure 4. Extracting inter-beat intervals (IBIs) from a photoplethysmograph (PPG) sensor. (a) Sensing principle. (b) Overview of signal processing. (c) Example results of IBI extraction in 30 seconds. The IBIs and beats are correctly identified from the raw PPG data.

Implementation and Evaluation. A Pulse Sensor Amped PPG sensor[4] is installed on one side of the pad for sensing. The central hole of the ball bearing has wires that connect the sensor an ATMega32U4 microcontroller attached to the other side of the pad. Each frame of raw PPG sensor data is retrieved and digitalized into a 10-bit integer value, ranging from 0 to $V_{ref} = 5V$ in the interrupt service routine (ISR), which runs steadily at 500Hz on the microcontroller; $\alpha = 0.2$ and $C = 0.6$ are chosen in our algorithm implementation. Figure 4c shows the example results of IBI extraction using our implementation. The user holds the device steadily during the 30-second data collection period. The IBI is successfully extracted for each 2 beats, which are also identified correctly.

[4]https://pulsesensor.com/

Activity Recognition through a Fidget Spinner

The essential activities that must be identified are the ones that cause the fidget spinner to spin. To detect these gestures from the spinning movement, magnetic sensing methods are employed, which account for several contextual factors, such as occlusion and lighting issues. Figure 5a shows an overview of the proposed sensing mechanism. An analog Hall sensor, which is attached to the center pad, is used for sensing the magnetic fields of magnetic components, which are placed on the wing. To keep the balance of rotation, an axially magnetized ring magnet, or at least two magnetic elements, should be placed in a rotationally symmetric way, centered on the center of the fidget spinner, so that the total torque remains zero when the wing rotates, keeping the rotation in balance. The contactless sensing mechanism also adds no friction to the fidget spinner. One of the magnets, M_{North}, poses its North pole face toward the sensor, whereas the others pose their south poles toward the sensor.

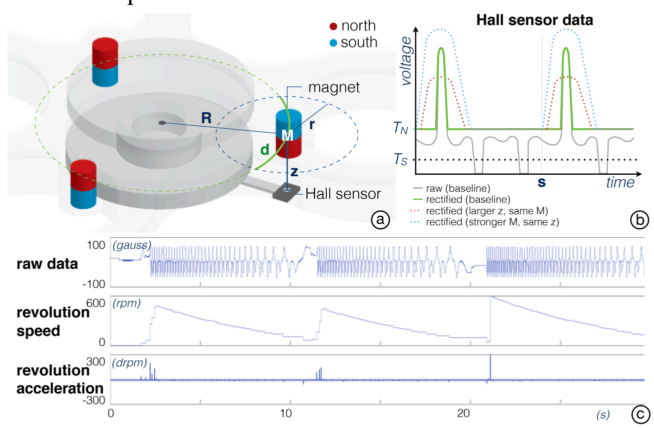

Figure 5. Geometry model of magnetic revolution sensing based on an analog Hall-sensor and 3 magnets (1 north and 2 south). (a) Overview of components. (b) Signal rectification on an example raw data. The outcome depends on the strength m of the magnet and its vertical distance z to the sensor. (c) Example results of signal processing in 30 seconds.

The revolution speed of the fidget spinner can be obtained from detecting the M_{North} only. Each sensor reading v' is rectified using the function $v' = max(v - v_0, T_N)$ (Figure 5b), where v is the original Hall sensor reading, v_0 is the neutral (0 gauss) reading obtained beforehand, and T_N is the north-pole intensity threshold. A rising-edge trigger ($v' > T_N$) detected immediately after a falling-edge trigger ($v < T_S$, where T_S is the south-pole intensity threshold) counts as 1 revolution, and the revolution speed can be obtained from a running average of revolution count. Then, we can extract the revolution acceleration, a clear indicator of the exerted force, from the slope of the speed curve.

The maximum revolution speed depends on the strength of M_{North} and its vertical distance z to the sensor. Figure 5a shows the geometry model, where R is the revolution radius, d is the length of revolution path that the M_{North} can be detected, and r is the radius of the intensity cross section of a magnetic field. Given s as the time required for a complete revolution of the spinner, the time t that a revolution would be detected can be modeled as

$$t = \frac{d}{2R\pi}s \sim \frac{r}{R\pi}s, \quad (1)$$

where an approximation $d \sim 2r$ is used for clarity of explanation. Two design guidelines are summarized: 1) The magnet and the sensor should be placed as close to the center as possible because a smaller R allows for higher speed of revolution to be captured. 2) Using magnets with larger radius allows a higher speed of revolution to be captured because the r values are large. However, the radius should not be too large, lest it affect the detection of the falling edge of the signal. Proper vertical distance z or intensity threshold T should be chosen to keep $r \leq \sqrt{2}R$. In the case of $r = \sqrt{2}R$, a 500Hz sampling of Hall-sensor readings can capture 7500 revolutions per minute (RPM) without information loss [30].

Implementation and Evaluation. A Winson[5] WSH137 analog Hall sensor and three 5mm-thickness $\times$ 2.5mm-radius N35 cylindrical neodymium magnets are used in the implementation. A 10-bit integer value in the range of ± 450 gauss, where a negative value indicates south pole, can be measured and synchronized with each frame i of PPG reading at 500Hz. $T_{north} = 65$ gauss, which is 100 times stronger than geomagnetism, is set to cancel out the effects of fidget orientation. As the measurements of the prototype are z = 6mm and $d \sim R\pi/2$, the theoretical maximum revolution sensing is $\sim$ 3750 RPM without information loss. Figure 5c shows the example results of *flicking* action extraction using our implementation. The user uses his dominant hand to hold the device steadily by pinching the center pad using the thumb and middle fingers, and spins the fidget by flicking the wing every 10 seconds. During the 30-second data collection period, the revolutions, speed, and acceleration were successfully identified. The peaks of acceleration corresponded to the exact timing of the flicking event.

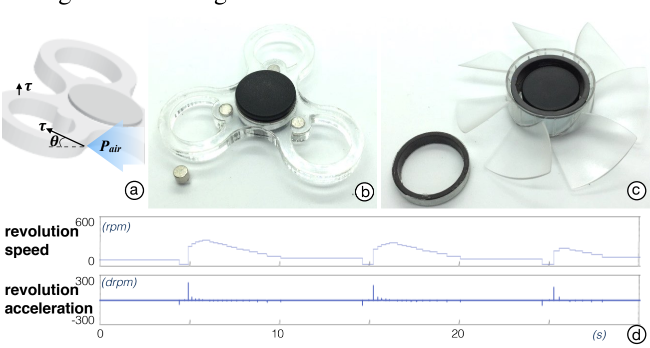

Figure 6. Wing designs for respiration sensing. (a) Geometry model. (b) 2D wing design embedded cylindrical magnets. (c) 3D fan-shaped wing design mounted on an axial-magnetized ring magnet. (d) Example results of signal processing in 30 seconds.

Sensing Respiration Using a Fidget Spinner

Just as a pinwheel rotates with a users breathing, an exhalation can spin a fidget spinner if the wing is properly designed for aerodynamics. Figure 6a shows a conventional form of a fidget spinner. An exhalation exerts the air pressure P to the wing surface, generating a torque at magnitude $||\tau|| = ||r \times P||cos\theta$, where r is the position vector the force is applied, P is the force vector, and θ is the angle between the P and the surface's normal vector. If the total $||\tau||$ is stronger than the rolling friction f of the ball bearing, the wing can be moved. Choosing a proper θ and expanding the surface area of the wind-stopper can increase the $||\tau||$.

Therefore, we propose a redesigned physical form of the wing for respiration training. Figure 6b shows an example of a 2D design with a hollowed out circular hole on each side of the wing to increase the surface area as a wind stopper, which preserves the original affordance of a fidget spinner so that the user can easily spin it by finger flicking. Figure 6c shows another design that exploits a 3D fan-shaped wing, which is optimized for receiving more energy in the wider range of angles θ. The weight reduction of these two forms allows the wing to spin faster, even when a minimal amount of force is exerted upon it. However, the form deviates from the original form of typical fidget spinners, so the user may not easily spin this fidget spinner using a single finger. Both designs mount at least one magnet for monitoring its revolution. Figure 6d shows the results of a user *blowing* on the 2D wing during respiration training using a consistent data collection protocol. The results show that the user can spin a static fidget spinner with a deep exhalation. The peaks of acceleration corresponded to the exact timing of the blowing event correctly. The velocity curve is smoother than that of flicking.

Activity Recognition. A simple yet effective algorithm was designed to detect and recognize the blowing and flicking actions from a static posture using the different acceleration patterns. In a frame i, when the revolution acceleration intensity A_i is higher than a threshold, the system detects the action and collects the velocity V_i of each frame i in the following s-second window. Then, the system identifies the time t_{max} of the maximum velocity from the complete collection. Either a blowing or a flicking can be recognized based on whether the $t_{max} < ks$, where $0 < k < 1$ is a heuristic constant.

Augmented Visual Feedback and Feedforward

The current device provides rich visual-tactile inherent feedback [6] for the exhaling, i.e., the acceleration and the vibration of the fidget spinner. However, the device neither provides further procedural information nor adapts to the users need for respiration training. To fill the gap, an extra display must be added to provide *augmented feedback* and *feedforward* to the interactive system.

Intuitive feedback and feedforward should coincide in modality, time, location, direction, dynamics, and expression [37]. Regarding *modality*, a visual display provides greater bandwidth of communication; therefore, we first consider bringing a simple yet rich visual display, a NeoPixel ring[6] that consists of 12 RGBW LEDs, to augment the fidget spinner. Regarding *location*, the display is set to the center of the fidget spinner, so the user can perceive the provided information without dragging his or her foveal attention away from it. The ring display is placed under the transparent wing so it augments the physical movement instead of replacing it.

[5] http://www.winson.com

[6] https://www.adafruit.com

Visual Augmentation for Respiration Training. The ring displays respiration-related information when the BioFidget spins within the recent 10 seconds (1 complete cycle of respiration). To guide the users to perform right *direction* of interaction at the right *time*, the visualization should clearly indicate the current state (i.e., mode), what to do next (i.e., feedforward), and the effects caused by the performed action (i.e., feedback). We choose three independent parameters: color channel, brightness, and hue, in which to present the information. In our respiration training, the ring indicates inhalation and exhalation using 2 independent channels, monochrome (pure White) and color (RGB), respectively (Figure 7a and 7b); the ring indicates breathing speed and timing t through a steady, linear function $brightness(t)$ in both modes as feedforward; the ring also indicates the revolution speed v as a feedback of exhalation quality using a colorful ring in a different range of hue through a linear function $hue(v)$ (Figure 7d) as

$$hue(v) = \begin{cases} [.25v,\ .75v] & \text{if } 0 \leq v < 1 \\ [0,\ 1] & \text{if } v = 1, \end{cases}$$

where both $hue(v)$ and v are clipped with bounds and normalized to $[0,1]$ for generalization. Finally, regarding *dynamics*, the colorful ring also rotates according to the speed of the fidget spinner (Figure 7c).

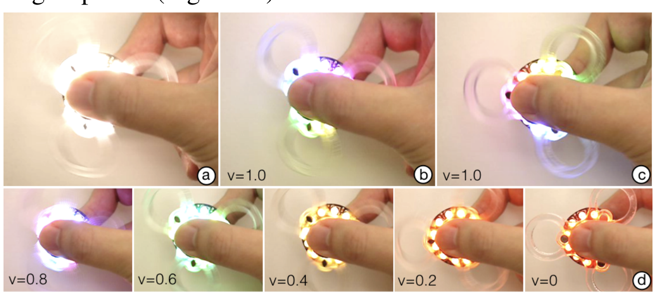

Figure 7. Visual augmentation for respiration training. (a) The pure-white ring indicates inhalation. (b) The colorful ring indicates exhalation. (c) The color ring rotates with the fidget spinner. (d) The hue and its range change according to the revolution speed.

Visual Augmentation for HRV Awareness. Before, or after, the respiration training, the device should display the users pulse and HRV information as feedback and feedforward for respiration training. Regarding the *direction* and *time* of interaction, if the BioFidget did not spin in the most recent 10 s, the BioFidget guides the user to place his or her finger on the green LED of the PPG sensor by turning the ring display off, and guides the user to wait by showing a loading animation. The *expression* of IBI and pulse information has two parts: a 10-scale monochrome bar showing the IBI between 500ms and 800ms in real time, and two fading red (colorful) LEDs to mimic the *dynamics* of a human pulse (Figure 1b).

Incorporating with a Portable Display

Portable displays can also be integrated to augment the visual feedback of BioFidget. These high-resolution displays can provide rich visual biofeedback expression, and the embedded sensors and actuators (e.g., speaker) can enrich the *modality* of interactivity and increase the level of embodiment. One of the best *location*s to place the BioFidget is on the screen so that the nearby visual feedback can directly augment the experiences of training. With reliable communication, the signals can be provided at the right *time*.

Figure 8a shows a user using a smart phone that produces the aforementioned visual display. The 4.7-inch retina display renders a high-resolution colorful ring, which preserves the features of *direction*, *dynamics*, and *expression* of the visual design introduced in the previous sections; moreover, the rich visual display is collocated with respiration guidance and feedback (Figure 8a and 8b), which the users can perceive simultaneously using both their foveal and peripheral vision; furthermore, it also provides *historical* HRV information (Figure 8c). Based on the principle of RSA [38], we designed a simple example of IBI visualization as biofeedback for respiration training. Figure 8d and 8e shows an overlaid IBI and revolution speed graph, which is drawn circularly in 1.2 rpm. The visualization shows the IBI with the fidget revolution speed in the last $N = 5$ breathing cycles. During the respiration training, the oscillation phases of IBI and the respiration synchronize as a five-petal flower on the screen (Figure 8d), which allows the user to evaluate the heart regulation with the visual feedback received from the respiration training. This infrastructure enables various forms of presentation, such as aesthetic, metaphorical, or poetic biofeedback [40].

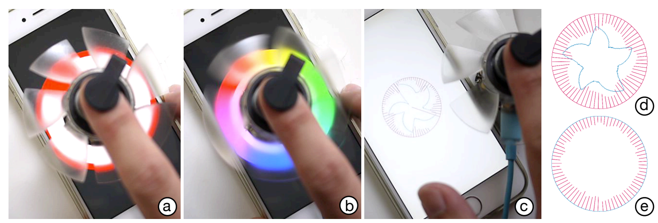

Figure 8. Smartphone implementation. (a) The progress of inhalation. (b) The progress and the quality of exhalation. (c) Visualization of HRV (red) and respiration (blue) information. (d) Results of an adequate respiration training. (e) Results without respiration training.

EVALUATION

A series of studies were conducted to understand the technical validity and the user experiences of the BioFidget prototype.

Common Apparatus and Tasks

Two basic BioFidgets, one with a clip (Figure 6b) and another without a clip (Figure 6a), were used in the study. Basic BioFidgets were chosen because the participants were more familiar with this form of fidget spinner. Additional hardware was used in this study for validation, including an ADXL335 3-axis accelerometer, which was added to the BioFidget prototype to monitor the motion patterns (Figure 2), and a secondary PPG sensor, which was worn on the users non-dominant hand while using the BioFidget prototype with the dominant hand (Figure 10). The secondary PPG sensor also simulated the static uses of BioFidgets, as shown in Figure 8. The 3-axis acceleration vector $\bar{a}_i = (x_i, y_i, z_i)$ and the secondary PPG readings were obtained and synchronized with each frame i of primary PPG reading at 500Hz. The acceleration intensity between each frame i is calculated as $A_i = ||\bar{a}_i - \bar{a}_{i-1}||$. The Neopixel ring display shows the designed visual augmentation as a visual guidance for respiration. To motivate the users to blow on the devices steadily

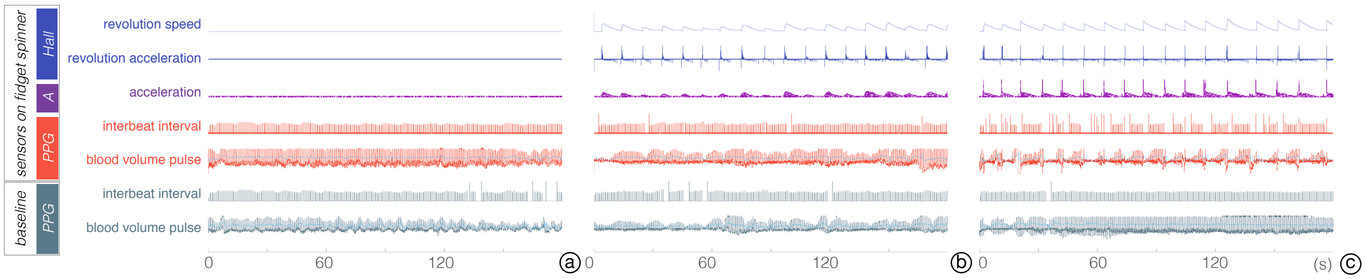

Figure 9. Sensor data stream collected from an example user who performs 3-minute respiration training sessions in three different ways. (a) *Normal*: the user only takes deep breaths. (b) *Blow*: the user blows on the fidget spinner by exhaling. (c) *Flick*: the user flicks the fidget spinner while exhaling.

to retain the colorful lighting effect, the visualization parameter v was tested and set to 500rpm so that colorful effects were easily achievable for the users. The devices were wire-connected to a laptop (Macbook Pro 2016) for data collection and power supply.

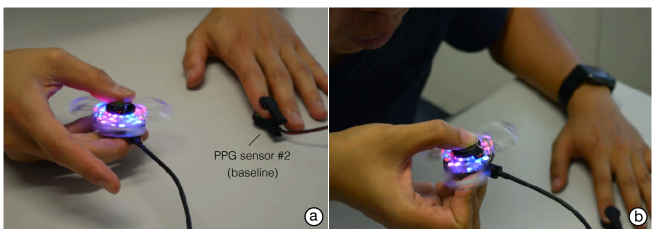

Figure 10. Two modes of respiration training and the experimental apparatus. A secondary PPG sensor is attached to the user for validating the PPG data on the BioFidget prototype. (a) *Flick*: the user flicks the fidget while exhaling. (b) *Blow*: the user blows on the fidget by exhaling.

Each participant received instructions on how to perform the respiration training, and how to play with a fidget spinner. Then, the participant performed 3-minute respiration training in two different sessions: 1) *Flick* (Figure 10a): the user *flicks the fidget while exhaling*, and 2) *Blow* (Figure 10b): the user *blows on the fidget spinner by exhaling*. The length of the session was determined based on the findings of Lin *et al.* [20], which suggested that the HRV power spectrum distribution of a 3-minute collection was similar to a 5-minute one. Before each session, they first practiced the uses in a flexible-length practice session. Then, they received a 3-minute *baseline* session where each participant was permitted freely browse internet using the dominant hand using a smart device when the secondary PPG sensor collecting the heart-rate information. The 3-minute *Flick* and *Blow* sessions allowed each participant to perform actions during the respiration training, so a total of $576 = 32 \times 18$ flicking and 576 blowing actions could be collected, respectively.

Pilot Study: Physiological Sensing Validity vs. Actions

Actions may interfere the heart-rate sensing, because the finger movement potentially changes the light reflection received by the PPG sensor. Because flicking and blowing actions potentially cause motion artifacts in the IBI data, we first conducted a pilot study with an example user to understand how the physiological sensing validity is affected by these actions. During the data collection, the user rested both arms, wrists, and palms on a surface to minimize the unwanted motion artifacts except for those from the performed actions. For comparison, he performed an additional 3-minute *Normal* respiration training session, where he held the BioFidget using the dominant hand and only exhaled. The data streams of all sensors were collected for post-hoc analysis.

Results and Discussion: Figure 9 shows the results. In the *Normal* and *Blow* the IBI records of the primary and secondary PPG sensors were similar and stable, showing that the beat detection algorithm was robust enough for extracting the IBI, even when the user was blowing on the spinner in a static posture. However, in the *Flick* session, every finger flicking deviates from the IBI data from the baseline because the intense motion (shown in the accelerator data) corrupted the BVP waveform, indicating that IBI information is motion-sensitive. This suggests that the IBI information should be discarded and hidden from the user when he is flicking the spinner. The results also imply that flicking and blowing actions should be classified for different treatments.

User Study: User Experiences of Respiration Training

This study aims to understand the user experiences of BioFidget in a realistic and casual setting. The participants were asked to use the device to perform two sessions of respiration training in a personally comfortable way *without* any experimental constraints.

32 participants (15 males, 17 females) aged from 26 to 41 (M=28.19; SD=1.63) were recruited for the study. All participants knew how to play with fidget spinners. Eleven participants had experience playing with fidget spinners. The participants were separated into two groups of equal size. One group went from the *Flick* to the *Blow* session, and the other group went from the *Blow* to the *Flick* session. For each group, 8 users used the BioFidget without a clip (Figure 3a), and 8 other users used the one with a clip (Figure 3b). After the introduction and practice sessions, they were asked to follow the two task sessions, following the visual guidance and feedback provided by the BioFidget prototype. After the two sessions, each participant was asked to describe relevant experiences through a short interview. The sensor data and user responses were collected for post-hoc analysis.

Quantitative Metrics and Data Analysis

Three quantitative metrics were used for system evaluation.

HRV Indices. Two common HRV indices, *LF/HF* (Low Frequency to High Frequency Ratio) and *RMSSD* (Root Mean Square of Successive Differences between heartbeats) were chosen as the HRV indices of stress [4] and heart rate regulation [34], respectively. *LF/HF* was the frequency domain HRV parameter, where the LF and HF powers of the

HRV were calculated as the area under the power spectrum distribution curve corresponding to 0.04-0.15Hz and 0.15-0.4Hz, respectively. Through breathing exercises, the IBI data was modulated into a stable, periodic sinusoidal pattern, at which point the ratio of the low-frequency components was increased and the amplitude of HRV was maximized. The increased *LF/HF* and *RMSSD* both showed a quality improvement of heart-rate regulation. An increased *LF/HF* also indicated a reduction of cognitive stress [4].

Beat Miss Rate. Heartbeats and IBIs were identified using the aforementioned heartbeat detection algorithm. Beat miss rate was calculated by the following procedure: 1) Identify the beats of an unnatural $IBI_u > 1250ms$ caused by the missing beats from the data, and count the number of these beats as B_u. 2) Calculate the $mean(IBI_n)$ of the remaining natural beats, and count the number of beats as B_n. 3) Convert each $IBI_{(u,i)}$ into equivalent missing beat count $B_{(m,i)} = IBI_{(u,i)}/mean(IBI_n) - 1$, sum them as $B_m = \sum_i^{B_u - 1} B_{(m,i)}$, and then obtain the beat miss rate $R_{miss} = B_m/(B_m + B_n + B_u)$.

Activity Detection and Recognition Rate. Activities were extracted using the algorithm mentioned in the previous Activity Recognition section. Nine different speed thresholds T_s ranging from 60 to 300 rpm and four different window sizes $W = \{200, 300, 400, 500\}$ were used for classification. Activities were recognized using a nearest-neighbor classifier in a five-fold cross validation, where each 1/5 of data were classified by a model trained on the rest of data.

Quantitative Results

Four main quantitative findings are summarized with results.

1. HRV Sensing was More Reliable in a Static Context. Figure 11 shows the beat miss rate of both PPG sensors. The Shapiro-Wilk tests indicated the beat miss rates were not statistically normal in all conditions of *Blow* and *Flick* session (all $p < 0.05$). In *Blow* session, results of a Mann-Whitney's U test shows a significant difference ($Z = -6.88$, $p < 0.001$) in the beat miss rate for using BioFidget ($Mdn = 3.2\%$, $SD = 4.71\%$) and the baseline ($Mdn = 7.5\%$, $SD = 19.2\%$) among all participants; In *Flick* session, the results show a significant difference ($Z = -6.92$, $p < 0.001$) in the beat miss rate for using BioFidget ($Mdn = 0.4\%$, $SD = 4.27\%$) and the baseline ($Mdn = 7.5\%$, $SD = 19.2\%$) among all participants. The low miss rates of the baseline PPG suggest that, in a static use, the HRV information collected by the baseline is generally more reliable than the one collected by the BioFidget. Hence, we first used the baseline for understanding the effects of respiration training before we considered how to enable more interactive uses.

2. Respiration Training was Effective in Both Flick and Blow Modes. Our primary goal was to determine whether respiration training is effective. Data collected from the baseline PPG sensor were used for analysis. Unnatural IBIs ($> 1250ms$) caused by the missing beats were removed before the analysis. Figure 12 shows the box plots of the *LF/HF* and *RMSSD* for the *Flick* session and the *Blow* session, corresponding to the baseline condition collected before each session. The Shapiro-Wilk tests indicated that neither *LF/HF*

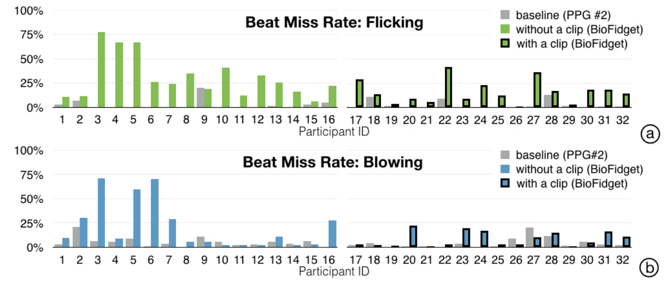

Figure 11. Beat miss rate of PPG sensing. (a) Flicking. (b) Blowing.

data nor the *RMSSD* data were statistically normal in all conditions (all $p < 0.05$). The results of a Wilcoxon Signed-rank test show a significant difference ($Z = 2.66$, $p = 0.008$) in the *LF/HF* for *Blow* session ($Mdn = 3.47$, $SD = 3.82$) and its baseline ($Mdn = 2.17$, $SD = 1.72$), and show a significant difference ($Z = 3.47$, $p = 0.01$) for *Flick* session ($Mdn = 4.01$, $SD = 6.02$) and its baseline ($Mdn = 2.07$, $SD = 2.11$). The results of the Wilcoxon Signed-rank test show a significant difference ($Z = -4.39$, $p < 0.001$) in the *RMSSD* for *Blow* session ($Mdn = 67.35$, $SD = 39.2$) and its baseline ($Mdn = 45.7$, $SD = 32.1$), and show a significant difference ($Z = -2.42$, $p = 0.016$) in the *RMSSD* for *Flick* session ($Mdn = 52.5$, $SD = 42.9$) and its baseline ($Mdn = 50.2$, $SD = 45.4$) . The *RMSSD* in *Blow* session was also significantly higher than the *RMSSD* in the *Flick* session ($Z = -2.1$, $p = 0.035$). The results suggest that both sessions of respiration training were effective in stress reduction, and blowing on the BioFidget was more effective than flicking for heart-rate regulations.

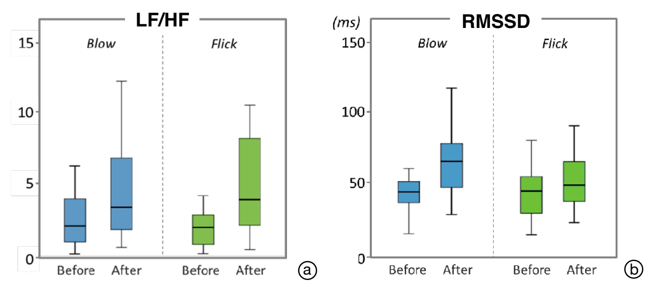

Figure 12. HRV results of respiration trainings. (a) LF/HF. (b) RMMSD.

3. Clip Stabilized the HRV Sensing and Enabled Blowing Input. The data collected from both PPG sensors during the study differed from the data drawn from the statistical significances during the study. The results of the Shapiro-Wilk test indicated that the beat miss rate was not statistically normal in all conditions. In the *Flick* session, the results of the Wilcoxon Signed-rank test showed a significant difference ($Z = -2.15$, $p < 0.05$) in the beat miss rate between a BioFidget with a clip ($Mdn = 14.1\%$, $SD = 11.8\%$) and one without a clip ($Mdn = 24.9\%$, $SD = 21.8\%$). In the *Blow* session, the nonparametric Wilcoxon test also showed a non-significant improvement ($Z = -1.21$, $p = 0.23 > 0.05$) in the beat miss rate between a BioFidget with a clip ($Mdn = 3.9\%$, $SD = 7.4\%$) and one without a clip ($Mdn = 9.4\%$, $SD = 24.8\%$). Notably, the performance with a clip condition was comparable to the baseline PPG sensor ($Mdn = 3.2\%$, $SD = 4.71\%$) even through the participants were blowing the BioFidget, showing that the HRV collected by the BioFidget with a clip has a reliability similar to that of the baseline in the Blow session. The use of a clip stabilized the HRV sensing by reducing the motion artifacts caused by hand trembling (when holding the devices in mid-air), the co-movement of thumb and index fingers, and the change of postures. Therefore, with a clip, the system only needs to *recognize the flick actions* during the respiration training and *discard the consequent motion artifacts in the HRV data*.

4. Actions were Reliably Recognized. Figure 13 shows the results of activity recognition. For the 1105 flicking (539) and blowing (569) actions that caused a $\geq$60 rpm (1 revolution per second) spin, a nearest-neighbor classifier achieved an 87.9% of accuracy (flicking: 86.9%; blowing: 88.8%) with a window $W = 500$ms in a five-fold cross validation. 93.6% flicking and 98.8% blowing actions performed by all participants were recognized with reasonable accuracy in this setting (Figure 13a). These high accuracies of recognition also show the system reliably distinguished the flicking from the blowing actions; thus the invalid HRV information caused by these *recognized* flicking actions can be *discarded*. Applying higher T_s increased the recognition accuracy and also made the recognition more responsive. For the 736 flicking (362) and blowing (374) actions that caused a $\geq$ 300rpm (5 rps) spin, a 94.7% of accuracy (flicking: 95.3%; blowing: 94.1%) with $W = 200$ms in a five-fold cross validation was achieved. Nonetheless, only a 62.8% of flicking and a 64.9% of blowing actions were recognized as valid events in this case (Figure 13b). The shorter response time allowed the system to react faster to the flicking action, thereby avoiding the corruption of HRV signal collection. Nonetheless, the high false negative rate of this setting may have required the users to exert more of an effort when performing the actions. Figure 13c shows that the recall of blowing recognition was higher than the recall of flicking. With a $T_s = 60$rpm and $W = 200$ms, the recall of blowing achieved 86.6%, whereas flicking only achieved 53.5% (Figure 13d). Applying a larger W and a higher T_s can further improve the recall of blowing (e.g., 97.3% on $T_s = 300$rpm and $W = 500$ms). The results suggest that the activity recognizer is readily reliable in distinguishing whether the action is blowing if the user only blows on the BioFidget. Adding a mode switch on the device enables this feature.

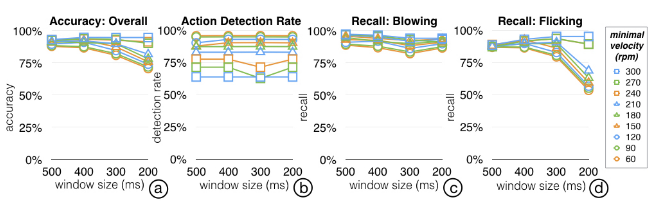

Figure 13. Activity recognition results. (a) Overall accuracy. (b) Action detection rate. (c) Recall of blowing. (d) Recall of flicking.

User Experiences

This section reports the responses from the interview conducted at the end of the evaluation. The responses indicated that the breathing training with the BioFidget was a playful experience. 31 participants (out of 32) reported that the breathing guidance through the light on BioFidget was clear and easy to perceive, as they were able to follow it in order to regulate their breathing pattern. 20 participants reported that spinning the fidget made them feel relaxed and more able to focus on the breathing guidance from the light changes, e.g., *"I feel immersed in the experience when I was staring at the device"* (P19). 26 participants stated that the colorful lights served as a feedback that engaged them with the BioFidget and motivated them to perform better in breathing training. For instance, some participants mentioned that *"it made me feel engaged and thus encouraged me to spin it faster,"* (P14, P23, P25) *"I preferred to see a colorful light instead of the red one, which motivated me to blow on it harder."* (P30, P31) and *"it was an amusing visualization and also a reward for my performance."* (P1). 17 participants also mentioned that the feedback with the colorful light during the fast spinning was enjoyable enough to enhance the playful experience with the BioFidget.

Regarding the interaction with BioFidget, 24 (without clip: 16; with clip: 8) participants prefer flicking to blowing because it is effortless. Nonetheless, participants reported that the clip made the flicking action difficult to perform. 19 participants stated that flicking actions, along with the breathing, made them focused and relaxed. For instance, some participant mentioned that flicking the fidget spinner is an action *"to release my stress"* (P8), *"clear my mind"* (P4), and *"make me more conscious about my breathing"* (P9). Nonetheless, the other 7 participants stated that they were not familiar with flicking the BioFidget using a single hand, so flicking it became a burden during the breathing regulation. 24 participants stated that blowing on the BioFidget helped them in breathing regulation. For instance, some participants mentioned, *"I breathed slower and deeper with its feedback. I believe it is helpful to adjust my breathing,"* (P9) and *"it helps in training my lung capacity"* (P1). The direct feedback from the fidgets spinning movement and its colorful light increased their consciousness of their own breathing pattern. 7 participants stated that the handheld form of breathing training was novel for them. For instance, participants mentioned *"I really like this tangible way to manipulating this device"* (P1),*"This innovation is based on the right object and its construction is highly functional"* (P15).

Some suggestions for the improvement of BioFidget were collected. 10 participants suggested that breathing guidance should be personalized and more adaptive, because they felt the 10 second breathing cycle of the respiration training was too long for them. 15 participants mentioned that it took a lot of effort to blow on the fidget spinner. 2 participants mentioned that moving the fidget spinner close to their mouths was slightly awkward.

Follow-Up Study: Fan-Shaped BioFidget with a Screen

A follow-up study was conducted to understand whether using a fan-shaped BioFidget could improve the user experiences. A subset of 20 participants from the previous 20 study (11 females, 9 males) were recruited again for this study. The mean age of the participants was 28.19 ($SD = 1.63$). All participants had experiences of using the basic BioFidget with or without a clip (Figure 3b or 3a, respectively). In this study they were asked to use the fan-shaped BioFidget (Figure 3c) for respiration training. Similar to the results presented in Figure 8, each participant was asked to place the fidget spinner on the screen of a Microsoft Surface Pro tablet, which was horizontally placed on a table, so users could place an index finger on the center pad of the fidget to use it. In accordance with the experimental protocols of the previous study, each participant received instruction before each session, performed a 1-minute baseline session, and then performed a 1-minute *Blow* session. The on-screen visualization (Figure 8) was provided during and after the respiration training, and the NeoPixel ring of the fan-shaped BioFidget was turned off; thus the users simply followed the on-screen guidance. After the two sessions, each participant received an explanation of the HRV visualization and was asked to describe the experiences through a short interview.

Results. According to the interview results, 18 (out of 20) participants reported that the fan-shaped BioFidget was easier to blow on than the basic BioFidget, and another two reported that they were equally easy to blow on. This result reveals that the fan-shaped BioFidget better supports effortless and smooth exhalation. 18 participants could tell the correlations between their breath and IBI patterns and agreed that respiration training could be helpful for heart rate regulation. Regarding the visualization, nine participants wanted to try it again because they wanted to improve their results. The results show that the combination of fan-shaped BioFidget and the on-screen feedback mitigates the previous concerns and provides engaging experiences.

DISCUSSION

Improving the Physical Design. The technology components are still visible in the current design. For casual interaction, the tether of the current hardware prototype should be removed. The current BioFidget prototype is a self-contained interaction device that comprises sensing, display, and computing capabilities. Therefore, optimizing the power consumption is necessary. The battery placement should preserve the original way of playing, rotational balance, and the inertial movement; in addition, the power should be sufficient to sustain the desired functions and the technical validity. A more embedded physical design and advanced manufacturing process that would conceal the sensors from the users perception would make the device look more like an everyday object: one that could easily be integrated into our daily life [35].

Extensions of the Biofeedback and Biosensing. The expressivity of biofeedback of the current implementation is limited by the 12 RGBW LEDs. An alternative design might use a high-resolution OLED Display or a persistence-of-vision (POV) display to provide richer information. One can also consider leveraging additional screens to provide contextual information in a higher level of embodiment: For instance, a smart TV or a vertical projection screen might be distant from the user, or a tabletop/tablet display might allow the user to spin a BioFidget on it and get detected [19]. One should also consider using ambient light bulbs, auditory displays (i.e., speakers), tactile displays, or shape-changing displays to augment the experiences further. Additionally, all the information shown on these displays should augment the fidget spinner instead of replacing it; otherwise the purpose of using BioFidget would deviate from the expressed purpose presented here. Regarding the biosensing validity, a customized electrocardiogram (ECG) sensor module could be more resilient to a motion and ambient light. A PPG sensor on a users earlobe could avoid finger motion, though it is an additional device that one needs to wear before fidgeting. These additional sensing mechanisms should retain the customary form factors for the original playfulness.

RSA Visualization in Training. For the consistency of user experiences, the smartphone screen only presents breathing guidance and feedback during the training as the screen-less one; therefore the RSA-like visualization is only shown as the history of a user's interest in the end of training. The results of an informal test with several users shows that they can perform breathing training correctly when they were watching the progress of the star-shape drawing, but as a side effect, it reduced the immersion of training because the user had to comprehend what the two curves might mean. Thus we recommend keeping the visualization as simple as possible and leaving its optimization for future work.

Advanced Intervention of Stress. This work demonstrates an adaptive and playful design intervention as a means of stress management for individuals. The user gets real-time biofeedback that closes the loop of the execution and evaluation [27]. However, a more sophisticated incentive mechanism should be considered to better facilitate long-term stress coping; this may be accomplished by motivating meaningful behavioral changes in users regarding problem-focused coping [25]. Multiple users can also use their own BioFidgets (either in a remote or collocated way) while their stress-related data are collected. This collective stress [17] information could be valuable for understanding the socio-technical issues within a group of users, which, in turn, could be used to help them cope with their common stressors and increase their productivity and health.

CONCLUSION

The fidget spinner is a popular toy that went viral in 2017. Although it is fun to play with, the general perception is that a fidget spinner is a useless machine which has a function but no direct purpose. Marketers sometimes claim that fidget spinners are a "treatment for people with attention-deficit/hyperactivity disorder, autism, or anxiety," and "a tool for focusing and relaxing." However, there is no peer-reviewed scientific evidence showing that fidget spinners are effective treatments for these conditions so far [29].

BioFidget integrates biofeedback, biosensing, and respiration training mechanisms into the form of a fidget spinner. The details of the physical, physiological, and visual designs have been disclosed. The results of technical and preliminary user testing also show that the proposed system and method provide valid and playful experiences that turn a popular toy into a useful stress management tool.

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