StressTree: a Metaphorical Visualization for Biofeedback-assisted Stress Management

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ABSTRACT
In today's highly competitive environment, chronic stress is one of the main reasons for a health problem. To address this, biofeedback techniques have been used to assist in relaxation training and stress management. In this paper, we present 'StressTree,' a metaphorical visualization of heart rate variability (HRV) biofeedback system. StressTree aims to present HRV data in a more evocative, meaningful way in the context of stress management. The HRV biofeedback system consists of a heartbeat data acquisition unit, a data analysis unit, and a visualization unit. The feedback from interviews in the evaluation shows that StressTree could display different growth pattern during a stressful work or a relaxation training. The participants suggested that the biofeedback interaction through StressTree is explicit and engaging, and brings them a strong motivation to regulate their breathing pattern for a 'healthy-looking' tree.

Author Keywords
Biofeedback; Metaphor; Visualization; Stress; Heart Rate Variability

ACM Classification Keywords
H.5.1 [Information interfaces and presentation]: Multimedia Information; H.5.2 [Information Interfaces and Presentation]: User Interfaces

INTRODUCTION
In modern society, fierce social competition leads to an increasing number of people suffering from chronic stress. Excessive stress that persists over an extended period may result in serious health problems including anxiety, insomnia, muscle pain, hypertension, and a weakened immune system [1]. The hazard of chronic stress is closely associated with the imbalance of the autonomic nervous system (ANS). The conditions will get worse the longer this imbalance persists. It is important to for individuals to realize their negative stress and cope with stress proactively.

As one of the most promising markers of ANS activity [2], Heart Rate Variability (HRV) is often visualized and presented to individuals, enabling them to be aware of the internal ANS activities related to stress responses. This process is commonly known as HRV Biofeedback. HRV biofeedback can be categorized into two classical approaches: representation of calculated HRV and representation of successive beat-to-beat intervals. In the first approach, biofeedback serves as a 'mirror' to improve the user's awareness of their stress levels. The calculated parameters of HRV, such as the ratio of LF/HF, can reflect the balance between the sympathetic and parasympathetic branches of ANS, indicating the stress level [3]. In the second approach, biofeedback serves as a 'crutch,' which assists the user's self-regulation in a relaxation training. For instance, the successive beat-to-beat intervals (also referred to as RR intervals or respiratory sinus arrhythmia, RSA) is widely used as the content of HRV biofeedback, which assists the users in learning resonant respiration for relaxation [4].

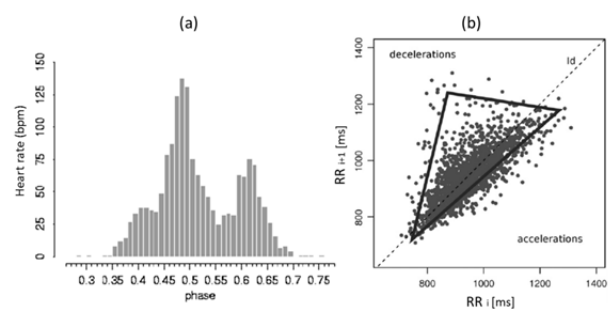

Figure 1. The clinical biofeedback visualizations of HRV data

Since the early 1970s, biofeedback techniques have been used in clinical settings[5], as a special intervention or treatment in cognitive or behavioral therapy. With the ubiquitous computing has been addressed in recent years[6], biofeedback devices become increasingly portable and affordable. Biofeedback information becomes easily accessible to casual users. Thus, biofeedback is not only the treatment of severe stress disorders[7] but also a tool for facilitating self-regulation in our daily life. These 'casual' biofeedback systems form a new branch of the biofeedback field: Ubiquitous Biofeedback (U-Biofeedback) [8]. In most

DIS 2017, June 10-14, 2017, Edinburgh, United Kingdom
© 2017 ACM. ISBN 978-1-4503-4922-2/17/06…$15.00
http://dx.doi.org/10.1145/3064663.3064729

clinical biofeedback systems, the visualizations of bio-data use 'medical' style that is designed for clinical staff, such as the RR intervals wave and Poincaré plots shown in Fig 1. In our view, the bio-data visualizations in U-biofeedback field should be more understandable, engaging, and more persuasive for casual users to use every day.

In this paper, we present a metaphorical visualization of heart rate variability (HRV) data for biofeedback. In the visualization of StressTree, the parameters of HRV data is mapped to the attributes of the abstract visual form (i.e. thickness, length, and direction of the bar) in real-time.The abstract visual form is then transformed into a metaphorical visual presentation that can present a slowly growing accumulative effect of stress responses or self-regulations. Metaphorical visualizations in biofeedback aim to present bio-data in a more evocative, meaningful and thought provoking way in the context of stress management. Our hypothesis is that the use of metaphor in visualization could translate the obscure bio-data into an image that is easy to understand and the biofeedback interaction through the metaphorical visualizations might be more motivated and engaging.

DESIGN OPPORTUNITIES

This study is initiated by problems arising during the design of the 'output' part of the HRV biofeedback system. In clinical biofeedback systems, HRV visualizations tend to be 'medical' and 'serious.' Most of the classical systems utilize numeric or graphic displays. *StressEraser* [4] guides the user to practice resonant breathing by presenting the RSA waveform back to the user, as shown in Fig 2(a). With the manual, this type of simple graphic display tend to be easy to understand, but it might also easily become boring and less attractive. More casual visualizations appear in ubiquitous biofeedback field. They become more 'playful' by gamification, or more 'artistic' by focusing on the amplification of the bodily experience. *Chill-Out* [9] is a casual biofeedback game for relaxation training. It is adapted from the game of Frozen Bubble by mapping the breathing rate to the game difficulty, see Fig 2(b). Many artists are also devoted to creating various biofeedback visual artworks. They focus on creating a new bodily experience with an abstract visualization through an immersive display. For instance, *Cardiomorphologies* [10] visualizes the breath and heartbeat data into a series of colorful rings, see Fig 2(c).

In our previous studies, some new presentations of HRV information have been explored, such as using circle maps [11] or ambient lighting [12]. Through those explorations, we learned that aesthetic qualities of visualizations are important to how the users 'feel' during biofeedback-assisted relaxation. We also found that the health-related information and meanings contained in physiological data are of the same importance, but not well expressed in most biofeedback visualizations. To solve this, here we turn to the use of metaphors in biofeedback visualization design.

Metaphorical visualizations map the characteristics of some well-understood visual images/patterns to a more poorly understood data source so as to render aspects of the target understandable[13]. Analogy and metaphor are considered as key aspects of human cognition [14]. Metaphors enable us to understand abstract information with familiar and well-understood images [15]. Visual metaphors not only help to present information but shape a specific meaning. A right visual metaphor can increase the expressiveness of information and define the context for correct interpretation of information and its meanings.

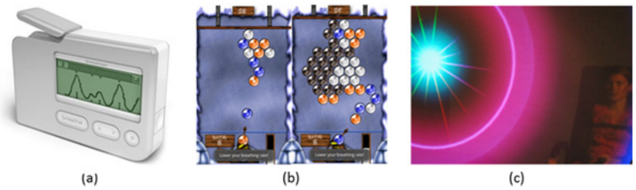

Figure 2. The visual interfaces in U-biofeedback design

In many literary works, trees are used as images typically associated with life and health, such as 'the Tree of Life.' A lush tree is often a symbol of a healthy person, in contrast; a withered tree represents an unhealthy state. Here, we use the image of the tree as a metaphor in visualization design, aiming to add a layer of meaning regarding the stress and health. In previous studies [16, 17], the metaphor od tree has been used in visualization of bio-feedback. In this study, we embarked on an interesting design journey, taking hints from understandings gained through the study of the autonomic nervous system, stress, and health, drawing metaphors into our design, ending up with a new interactive visualization of HRV named StressTree.

DESIGN CASE: STRESS TREE

The initial concept of StressTree was to transform the stress-related HRV data into an image of a tree, which metaphorically represents the health of the user, as shown in Fig 3. When a user suffers from excessive stress at work for a long period, the tree will become increasingly fragile and show a sub-healthy pattern. When the user is in the right balance of stress in life, the tree will grow up strong and looks more healthy. During the growth of the tree, the growing pattern can be affected by users' stress state, and it is possible for the user to manipulate the way the tree develops by relaxation training, such as deep breathing.

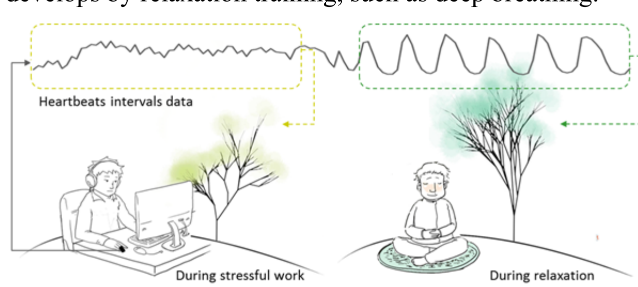

Figure 3. The concept of StressTree

Two approaches are experimented in the design of the 'StressTree.' The first one is the static L-system-based tree, which is generated by the calculated HRV data over a period, showing a long-term stress state. The second one is an interactive growing tree generated with the individual's real-time RR intervals data. It is designed as an alternative of the graphic display of RR intervals data shown in Fig 2(a).

Biofeedback System

Figure 4 shows the framework of our HRV biofeedback system. The pulse signal is measured by a PPG sensor placed on the left index finger. The sensor is connected to an *Arduino* board as a unit for data acquisition. The program on Arduino processes the raw pulse signal into beat-to-beat intervals (RR intervals), and then transmits the data to the PC through a USB serial port. The PC runs the visualization program (developed based on the *Processing* programming environment), transforming the RR intervals data and calculated HRV data into an image of a tree in real time.

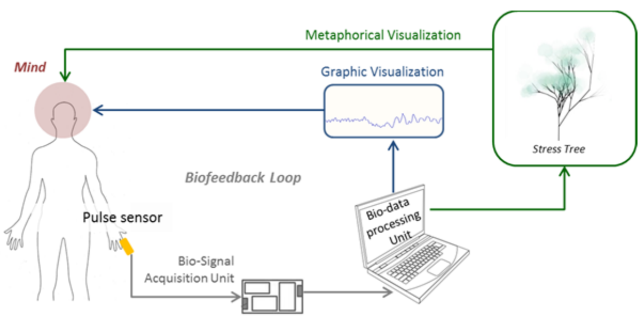

Figure 4. The framework of HRV biofeedback system

L-system based StressTree

Lindenmayer systems (L-systems) have been used as a foundation for plant modeling since the early 1970s. According to the theory of L-systems [18], tree development can be controlled by one production or a set of productions that describe the fate of plant components over discrete time intervals. Productions replace all modules of the predecessor tree in parallel derivation steps. This parallelism is intended to reflect the simultaneous progress of time in all parts of the modeled tree. The development of StressTree begins with a single segment and is modeled using one simple production: $A \rightarrow A\ (-A)\ (+A)$ with A as the initial state. The symbols '+' and '-' mean that the next move should turn right and left by an angle.

The shape of L-system StressTree represents the overall stress state over a period. In this study, we use the basic HRV analysis in the time domain as the indicator of user's stress level. The *SDNN* (the standard deviation of RR intervals) is calculated over a 10-minute period. According to the literature [19], the normal reference range of *SDNN* is from 100 to 180 *ms*. *SDNN* value is mapped to three parameters of the visualization: the thickness of the initial structure, scale factor and rotation angle of each new segment. The range of the initial thickness is 5 to 10 pixels, and the scale factor ranges from 0.6 to 0.8. The branches turn left or right in an angle between the ranges from $\pm PI/8$ to $\pm PI/4$. Thus, the larger the *SDNN* contributes to the thicker and longer branches with more straight and upward growing direction. In an iterative procedure, subsequently generated branches will be scaled down and rotated. The number of iterations is fixed at ten. As shown in Fig 5, with a low HRV (*SDNN*<60 *ms*), the StressTree looks small twisted and fragile; in contrast, a high HRV (*SDNN*>120 *ms*) makes the tree thrive, growing tall and lush.

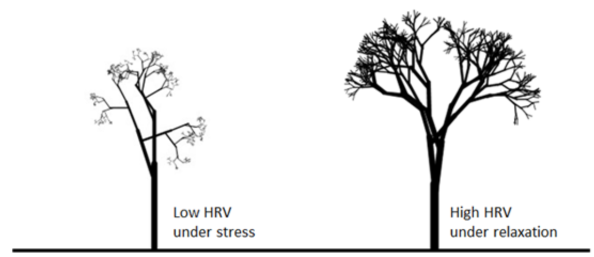

Figure 5. The L-system based StressTree

Interactive growing StressTree

To assist the user's relaxation training, an interactive StressTree was designed to present the RR intervals data in real time. Thus, the users could control the growth of StressTree through self-regulation, such as deep breathing exercises. The growth of StressTree also visualizes the process of relaxation training and its cumulative effect on stress reduction.

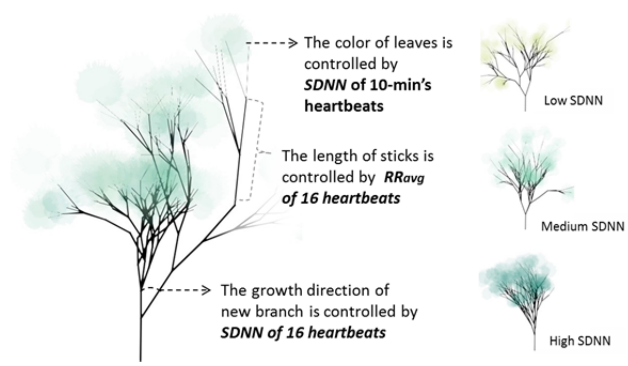

Figure 6. The interactive StressTree

Two parameters of HRV (RR_{avg} and $SDNN_{16}$) are calculated based on a moving window of 16 heartbeats. RR_{avg} denotes the average of RR intervals in the window; the formula is as follows: $RR_{avg} = (15 \times RR_{avg} + RR)/16$. In the calculation of real-time $SDNN_{16}$, we use the following formula: $SDNN_{16} = ((15 \times SDNN_{16} + |RR - RR_{avg}|)/16)$. The *SDNN* of the whole measurement over the 10 minutes is calculated for rendering the color of leaves at the end of visualization. The normal reference range of RR_{avg} and $SDNN_{16}$ are selected as 600-1000 ms and 100-180 ms respectively [19]. The rules in the generation of the tree are shown in Fig 6.

The growth of StressTree is triggered by the user's heartbeat. The attributes (length, thickness, and direction) of the new branch is updated by the HRV parameters of the coming heartbeat data. Each heartbeat brings one growth opportunity in one node, and the number of the split, the length, and direction of the branch in one growth depends on the updated $SDNN_{16}$ and RR_{avg}. Specifically, $SDNN_{16}$ data determines the number of the split at one node. When $SDNN_{16}$ is less than 60 ms, no new branches is sprouted. Instead, higher $SDNN_{16}$ gives more opportunities of sprouting (up to 3 at each node). The RR_{avg} is mapped to the length of branches. Under long-term stress, an individual's RR_{avg} rarely changes (e.g. around 650 ms); by contrast, RR_{avg} varies widely (e,g, ranging from 600 to 1200 ms) when the individual is relaxed. Especially during deep breathing, the RR_{avg} will change in an approximately sinusoidal form. Therefore, a sequence of flexible RR_{avg} yields a much richer hierarchy of branches.

Besides, $SDNN_{16}$ is also mapped (via the map function) to the range of rotation of each branch. In the initial stage of growth (here we set to 4 minutes), bigger $SDNN_{16}$ makes a smaller angle of branch's spread ($-PI/8$ to $PI/8$), making branches growing upward. In middle and last stages, bigger $SDNN_{16}$ makes large rotation angle ($-PI/4$ to $PI/4$), making branches spread out widely. At the end of the period, the overall *SDNN* of the whole period determines the color used for the leaves rendering. The color ranges from yellow-green to dark green, and the deeper the color represents, the higher average HRV level, the better state of relaxed.

INITIAL EVALUATION

To test the feasibility of StressTree to present stress state under different situations, we did the initial evaluation with ten participants. For each participant, the heartbeat data was measured and visualized in two conditions: 10-minute stressful work and 10-minute relaxation. The evaluation was conducted in a simulated working environment. To not interrupt participants' regular work, the StressTree was projected onto the office's wall, as shown in Fig 7. At the end of the study, we conducted the follow-up interviews with a focus on the following questions: *"Can you discern the information about your stress level through StressTree? Do you think StressTree is helpful to inform you of your stress level during the work? Do you think StressTree is helpful during the relaxation training?"*

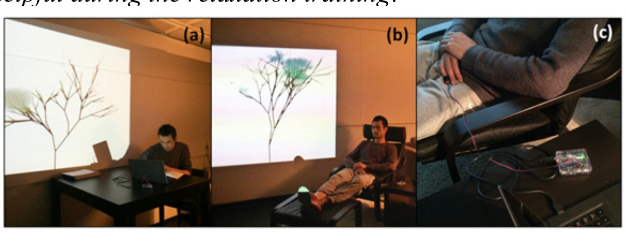

Figure 7. User evaluation (a). during the work (b). during relaxation (c). the pulse sensor on the finger

Fig 8 shows the StressTrees from 9 participants collected during stressful work activities and during the relaxation training. The shape of the collected StressTree varies from a small and crooked tree to a tall and upward-growing one with more branches and dark green leaves. The comparison between these two groups of StressTrees shows the impact of the chronic stress on our health in a more meaningful way. The feedback from interviews shows that StressTree has the potential to be a visual representation of stress level but also a real-time feedback of RR intervals data for biofeedback-assisted relaxation training.

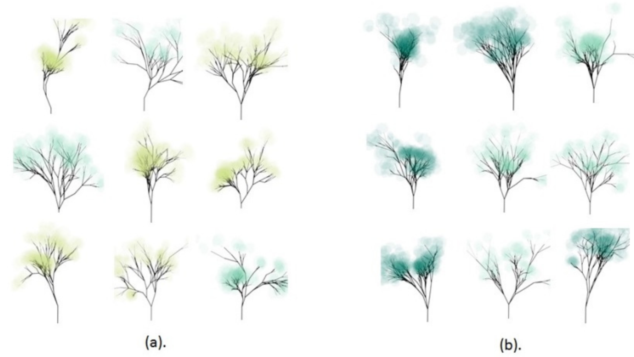

Figure 8. The collection of StressTrees (a). during a stressful work (b). during a relaxation training

Firstly, the participants reported that the visualization of StressTree was easy to understand. It is natural to link the 'health' of the tree to their stress level. Secondly, most participants thought that the projection of StressTree on the wall is an acceptable way of stress intervention. However, they were also concerned about the privacy of personal data visualization. They suggested that StressTree might be more suitable for visualizations on a smartphone, especially for a long-term stress management. Thirdly, the participants thought the feedback through StressTree during the relaxation training helped them to focus, reduced negative thoughts and clear the mind. They expressed that "*watching the StressTree growing is a relaxing thing*." Besides, some participants also mentioned that the StressTree brought them a strong motivation to regulate their breathing pattern for a 'healthy-looking' tree. Some participants also reported that the shape and color of the StressTree promote their self-reflections on their behaviors and experience during the experiment.

CONCLUSION AND FUTURE WORK

In this study, a tree-shaped metaphorical visualization was designed to present individuals' heart rate variability data for stress management. Our explorations have shown that it is very promising to visualize physiological data in the form that can express health-related meanings by using a well-fitting metaphor. For future research, we are considering two main directions. StressTree is our first attempt to present bio-signals into a more natural form. Based on the features of different bio-signals, various objects or processes in nature could be used in the creation of visualization to express specific meanings of the physiological information. Secondly, more parameters could be extracted from the raw physiological data based on more methods of data analysis. As mentioned above, HRV analysis in frequency domain also yields much information about autonomic balance. In a future study, we will visualize more aspects of stress using the approach of metaphorical visualization we explored in this study.

ACKNOWLEDGMENTS
We thank all the participants of the experiment, and all colleagues in Designed Intelligence group for their support and help with the study. We would also like to thank China Scholarship Council for support with the research.

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