Sonic Respiration: Controlling Respiration Rate Through Auditory Biofeedback

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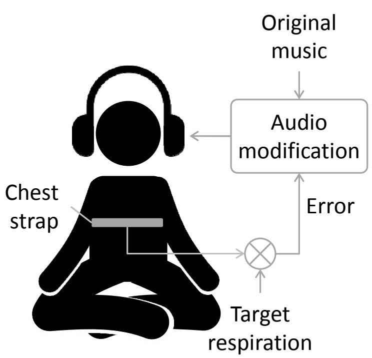
Abstract
We present an auditory biofeedback technique that may be used as a tool for stress management. The technique encourages slow breathing by adjusting the quality of a music recording in proportion to the user's respiration rate. We propose two forms of acoustic degradation, one that adds white noise to the recording if the user's breathing deviates from the target rate, and another that reduces the number of channels in a multi-track recording. Validation on a small user study indicates that both techniques are equally effective at reducing respiration rates while performing a secondary task, though user feedback indicates that additive noise is a more intuitive form of sonification.

Author Keywords
Respiration; biofeedback; sonification; ambient

ACM Classification Keywords
H.5.2. User Interfaces – Auditory (non-speech) feedback; J.3. Computer Applications – Life and medical sciences - Health

Introduction
Job stress has turned into a global epidemic. It can have serious health consequences for workers and large economic costs to their employers. As an example, stress is a risk factor for cardiovascular disease, the



Sonic Respiration teaches users to slow down their breathing while they enjoy their favorite tunes. Rather than using a pacing signal, Sonic Respiration manipulates the quality of the music to guide users towards a breathing rate that maximizes their heart rate variability (HRV).

leading cause of death in developed countries, and can have negative effects on mental health. Job stress also reduces worker productivity, and has been estimated to cost $300 billion to the US economy alone [1].

Several techniques may be used to help individuals reduce the impact of stress, such as meditation, deep breathing and biofeedback [2]. Among these, deep or diaphragmatic breathing (DB) is an easy and intuitive evidence-based method for stress management [3]. DB addresses the autonomic nervous system (ANS) imbalance that arises following exposure to a stressor and activation of the sympathetic 'fight-or-flight' response. As DB recruits the parasympathetic ANS branch, action of the sympathetic branch becomes inhibited leading to a calmer, more relaxed state. Many of the stress management programs delivered in workplace settings demonstrate that DB substantially reduces the symptoms of stress [2]. As with many other stress-management interventions, however, DB requires a substantial time commitment [4].

This paper presents Sonic Respiration, a biofeedback tool that may be used to make the DB practice more appealing and pleasant to the user. Sonic Respiration allows the user to perform DB while enjoying their favorite sound track. As their respiration approaches a breathing rate with known therapeutic benefits (6 breaths per minute (bpm); see System Design), the quality of the sound improves. In this fashion, users are encouraged to slow down their breathing and maintain it. We tested two implementations of the approach, one that increases the amount of additive white noise as the user's breathing deviates from the target rate, and a second implementation that reduces the fullness of the audio track by eliminating channels in a multi-track recording.

In the sections that follow, we review prior work on auditory biofeedback, music therapy and ambient displays for relaxation practice. We then describe the implementation of Sonic Respiration and present results from a pilot study. The article concludes with directions for future work.

Related Work

The connection between music and emotion has been known for thousands of years. Music allows artists not only to convey their emotions but also elicit an emotional response in the audience. Various forms of chant have evolved across cultures (from aboriginal cultures to the Buddhist and Christian traditions) to induce a heightened state of awareness, stabilize attention, control intrusive thoughts, and treat chronic illness [5]. Music therapy has also been shown to be an effective treatment for a variety of neurological and psychiatric disorders, including stroke, dementia, and depression [6].

Reynolds [7] showed that music can be an effective self-regulatory mechanism to reduce arousal. The study compared four types of relaxation techniques, a biofeedback-only treatment (BF) in which participants could hear a clicking noise that was related to their EMG signal, a music group (MU) that listened to harp chamber music, a group that listened to autogenic training phrases (ATP), a group that listened to the music and phrases (MU&ATP), and a control group. Results showed that the MU condition was far more effective than BF in reducing arousal (as measured by EMG response on the frontalis muscle), and far more

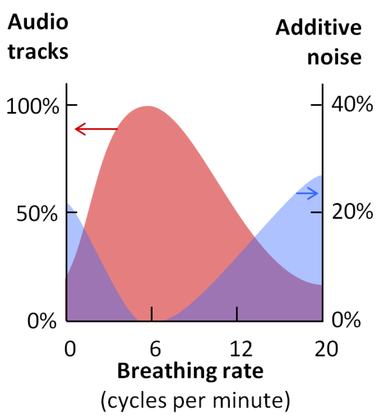


Figure 1: Relationship between breathing rate and audio quality for the track layering (left axis) and noise addition (right axis). Audio quality is maximized at and near 6 breaths per minute, and gradually degrades as the user gets further from the optimal breathing rate. For the track-layering manipulation, the app plays 100% of the tracks when the user is at the optimal breathing rate, and drops 50% of the tracks at 12 breaths per minute. For the noise-manipulation technique, the music plays with no additive white noise at and near 6 breaths per minute; at 12 breaths per minute, white noise at 10% of its maximum amplitude is added to the music.

effective than ATP in reducing the EMG response to a subsequent stressor.

Gavish [8] developed an auditory biofeedback device (RESPeRATE, InterCure, Inc., Montclair, NJ) for the treatment of hypertension. RESPeRATE provides an embellished auditory pacing signal with different tones for the inhalation and exhalation phases. The device measures the user's breathing rate with a chest-worn sensor, and delivers the auditory feedback via headphones [4]. The auditory pacing signal is initially synchronized to the user's breathing rate, but is gradually reduced to guide the user towards a slow breathing rate. RESPeRATE has been shown to lower blood pressure in subjects when used alone or with other treatments [4]. However, RESPeRATE uses a set of predetermined auditory tones and does not allow users to choose/personalize the biofeedback audio signal; it also uses a dedicated hardware device, which makes it less practical for ambulatory settings.

Moraveji et al. [9] presented BreathTray, an ambient display to incentivize calm respiration. BreathTray measures the user's breathing rate with a USB thoracic strain gauge, and displays it on the system tray. To evaluate the device, the authors conducted a user study where participants had to complete two different tasks that induce cognitive load. When compared against a control, BreathTray reduced breathing rate without any negative impact on task performance. BreathTray visualizes respiration rate through a peripheral display. In contrast, our proposed method uses auditory feedback and, more importantly, guides the user towards achieving a slow-deep breathing rate.

System Design

Motivated by this prior work, we set as our goal to design a system to promote slow breathing by means of auditory biofeedback; the system would not require external hardware beyond an inconspicuous wearable sensor, it could be used anytime/anywhere, and it would allow users to personalize auditory feedback to match their music preferences.

Our final design, Sonic Respiration, consists of an Android app running on a smartphone (HTC EVO 4G) with Android 2.3.3 that communicates with a Bluetooth-based thoracic respiratory sensor (BioHarness, Zephyr Technology Corp.) The app provides audio output that is modified depending on the user's breathing rate. We implemented and then evaluated two auditory modification techniques: track layering, and noise addition. The relationship between the user's breathing rate and the two audio modifications is illustrated in Figure 1.

The track-layering technique phases audio channels in/out from a multi-track recording. When the user breathes at a target slow rate (defined as 5.5–6.5 bpm) the audio contains all the channels in the recording. As the user gets further from this rate, channels are incrementally phased out, reducing the richness of the audio; these channels are added back as the user returns to the proper breathing rate. The phasing is done seamlessly without any noticeable audio artifacts. Track layering requires multi-track recordings, where each instrument is recorded in a separate track. This makes the technique ill-suited for personal audio collections, which generally consist of commercial stereo recordings.

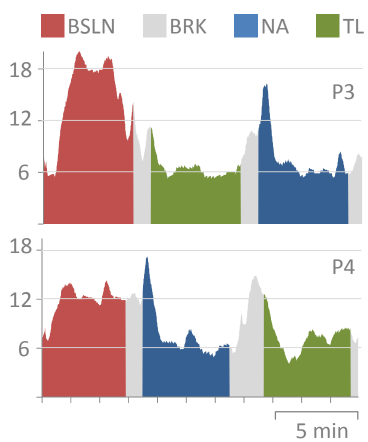


Figure 2: Temporal evolution of the respiratory rate for two of the participants in our study (P3, P4). BSLN: Baseline; BRK: Break; NA: Noise addition, TL: Track Layering.

As the name suggests, noise-addition adds white noise to the audio recording. When the user is at the target breathing rate, the audio contains no white noise. The more the user deviates from this rate, the higher the amplitude of the white noise, which in turn reduces the perceived quality of the recording. In contrast with track layering, noise-addition can work with any recordings in the user's personal music library. This provides maximum customization and the ability to practice for long periods without repeating the same audio track(s) over and over.

Our choice of a target rate of 6 bpm is motivated by prior psychophysiological studies [10], which indicate that heart rate variability is maximized when the breathing cycle has a duration of 10 seconds (i.e., a breathing rate of 0.1 Hz or 6 bpm). Our prior work [11] has also shown that this target breathing rate reduces arousal levels, as measured by heart rate variability (HRV) and electrodermal activity (EDA).

Study Design

We administered a user study to evaluate the effectiveness of the two audio manipulation techniques at lowering respiration rates. We compared these results against the initial respiration rate of the users, which served as the baseline.

For the study, we used the same song for both conditions and for all subjects. The song chosen was 'On the Line' by James May. The recording contained 14 tracks, of which two were vocal and were omitted to ensure that the song did not interfere with a secondary task (reading). The full track (remaining 12 channels) was used for the noise-addition manipulation. To simulate a typical work scenario, users were given a piece of literature to read while using Sonic Respiration. For this study, the book "Sweets: A History of Candy" [12] was provided, which was chosen as to not cause any external arousal.

Procedure

Participants (N=6; 2 males; ages 20-59) were informed of the process of the study, and then completed a consent form if they were willing to participate. The experimental protocol consisted of the following steps:

- Calibration (2 min). Participants were allowed to practice slow breathing at the optimal rate of 6 bpm using a free Android app (Paced Breathing) that provides an audiovisual pacing signal.
- Baseline (5 min). Participants were asked to read the provided literature while their baseline respiration rate was collected.
- Treatment 1 (5 min). Participants used one of the two Sonic Respiration modifications while they continued to read the provided literature. Order of presentation of the two modifications was counterbalanced across participants.
- Break (2 min). Participants took a break from the reading and the Sonic Respiration app.
- Treatment 2 (5 min). Participants used the second Sonic Respiration modification while they resumed reading of the provided literature.
- Survey. Users completed a short survey regarding their perceived effectiveness of the app, and their attitude toward each audio manipulation technique. This survey also contained basic health data, familiarity with relaxation techniques, and the user's opinion toward the study, biofeedback, procedure, and choice of wearable sensor.

Results

Sonic Respiration Impact on Breathing Rate

The first research question our analysis serves to answer is "Does Sonic Respiration feedback lead to a reduction in breathing rates?"

Experimental results are summarized in Table 1. Respiration rates with Sonic Respiration were lower than those at baseline, regardless of the auditory manipulation. Differences between baseline and either manipulation were statistically significant (BSLN-NA:p=0.007; BSLN-TL:p=0.010; paired t-tests)

	Breathing rate
Baseline	13.54 (2.38)
Noise addition	8.47 (2.81)
Track layering	8.18 (2.30)

Table 1: Average breathing rate and standard deviation (SD) for the three experimental conditions. Breathing rates were measured during the second half (2.5 min) of each experimental block to avoid the initial transient – see Figure 2.

The second research question was "Which audio manipulation leads to the lowest respiration rates?" Respiration rates for the track-layering condition were lower than those in the noise-addition condition, but the difference was not statistically significant (BSLN-TL:p=0.68; paired t-test). As we will see in the next section, however, most users felt that Additive Noise was more effective than Track Layering.

Figure 2 shows the evolution of the respiration rate for two of the study participants. During the baseline phase, the breathing rate doubles and triples from the optimal rate of 6 bpm (as practiced during the initial calibration phase). During the second phase, both participants are able to bring their respiration to the optimal rate and maintain it. The same result is observed during the third phase. The spike at the beginning of the three phases suggests that the participants are not used to breathing at the slower rate, so in the absence of a pacing signal (as is the case during baseline or the breaks), their breathing tends to return to a higher rate.

Qualitative Feedback

Analysis of the surveys shows that most participants preferred Noise Addition over Track Layering. Participant P2 wrote: "*The white noise was more noticeable and was more effective in helping me regulate my deep breathing*". Participant P1 shared this sentiment: "*I felt that the 2nd (white noise) was more effective. This one was clearer in alerting me of poor breathing. The other was easy to be confused with thinking what was playing with bad breathing was simply the normal song.*"

When asked if using the app made users feel good, participant P2 commented: "*Yes. More relaxed*" which was similar to participant P1's response: "*Yes the app makes me focus on my breathing, calming me down*". Similarly, participant P4 noted: "*Yes, I felt good by breathing correctly. Calm, relaxed*."

Most participants reported that they would use the app regularly, with timeframes ranging from P3's "*4-6 times daily*" to P4's "*Maybe every couple of weeks,*" with "*daily*" being the most common answer. Participant P1 suggested using the app "*…at work, to improve my productivity*" whereas P3 would use it "*before meetings, short work breaks, before driving,*" and P6 "*while running*," the latter an application scenario that we had not considered.

Discussion

We have presented preliminary results that suggest Sonic Respiration may be an effective tool to help users lower their respiration rates. Our results show that users were able to reduce their respiration by over 40%, in many cases reaching the target rate of 6 breaths per minute. The two acoustic manipulations appear equally effective at lowering respiration rates, though user feedback indicates that Noise Addition is a more intuitive form of respiratory sonification. As noted by the participants, the Track Layering technique requires familiarity with the song in order to determine whether all the tracks are being played.

Additional work is needed to validate the approach on a larger sample size, and establish dosage and persistence effects. Though slow/deep breathing often leads to relaxation, future experiments will need to assess the effectiveness of Sonic Respiration by measuring changes in HRV and EDA, as we have done in prior studies [11]. Future work will also test the effectiveness of different music genres in eliciting slow breathing patterns. A few participants indicated that the wearable sensor was bulky and inconvenient; work is underway in our group to eliminate the need for an external sensor by measuring respiration directly from the smartphone camera via photoplethysmography.

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