Music-based respiratory biofeedback in visually-demanding tasks

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ABSTRACT
Biofeedback tools generally use visualizations to display physiological information to the user. As such, these tools are incompatible with visually demanding tasks such as driving. While auditory or haptic biofeedback may be used in these cases, the additional sensory channels can increase workload or act as a nuisance to the user. A number of studies, however, have shown that music can improve mood and concentration, while also reduce aggression and boredom. Here, we propose an intervention that combines the benefits of biofeedback and music to help users regulate their stress response while performing a visual task (driving a car simulator). Our approach encourages slow breathing by adjusting the quality of the music in response to the user's breathing rate. We evaluate the intervention on a 2×2 design with music and auditory biofeedback as independent variables. Our results indicate that our music-biofeedback intervention leads to lower arousal (reduced electrodermal activity and increased heart rate variability) than music alone, auditory biofeedback alone and a control condition.

Author Keywords
Respiratory biofeedback; stress; music; driving

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

1 INTRODUCTION
Biofeedback techniques have been effectively used to manage stress [30] and treat anxiety [25, 33]. Biofeedback works by measuring physiological variables (e.g., heart rate, electrodermal activity), then displaying them to the user to improve self-awareness and self-regulation. Once limited to the confines of psycho-physiology labs, biofeedback can now be implemented in real-world settings owing to advances in wearable sensors and mobile technology over the past decade. Biofeedback interventions generally use visual displays of physiological information. As such, they demand visual attention from the user, making them incompatible with many routine activities such as driving, a common situational stressor in daily life. Though biofeedback can be provided through audio, e.g., by changing frequency, amplitude or pitch of an audio tone [1, 24, 33], this type of display is monotonous and can lead to frustration [15].

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By comparison, listening to music is engaging and can be an effective self-regulatory mechanism for arousal [21]. Music is also compatible with visually-demanding tasks such as driving. Not surprisingly, listening to music while driving is a popular activity: according to a 2014 report by Nielsen [3], nearly a quarter of all music listening in the United States happens behind the wheel. Considerable research has been carried out to understand the effects of music on driving performance: studies have shown that music improves mood [27, 28] and concentration [28], while reducing driver aggression [10, 34] and boredom [26].

In this paper, we propose an intervention that combines the benefits of biofeedback and music to teach deep breathing skills. Our intervention consists of monitoring the user's respiration rate and adapting the music quality (e.g., signal-to-noise ratio) to promote slow, deep breathing, an exercise with known therapeutic benefits [31]. We evaluate our intervention in the context of driving a car racing-simulator, and compare it against auditory biofeedback and music in terms of its ability to lower arousal levels. The originality of this study lies in using music quality as form of ambient biofeedback and evaluating it in the context of a visually demanding task.

2 RELATED WORK

2.1 Driving, stress and music
High stress impairs decision making, decreases situational awareness and degrades performance, all of which affect driving capabilities [14]. In addition, stress experienced during commuting has negative impact on health and work life [13]. Extreme stress can result in car accidents, and potentially property damage, medical costs, insurance costs, loss of work productivity, and loss of human life. The National Highway Traffic Safety Administration estimates that the US economy incurs over $230 billion of annual losses due to car accidents [10].

The effects of music on driving have been studied extensively. Zwaag et al. [27, 28] showed that music can positively influence driver mood and driving performance. Studies have also shown that music lowers driver aggression [34] and improves defensive driving [10], which directly reduces road rage –one of the main causes of fatal accidents. The extent of relaxation depends on the user's music preference, music genre (generally classical or instrumental) [5, 9], music properties (tempo, rhythm, volume, lyrics), age and type of intervention [20]. Music also improves performance during long monotonous driving sessions, where the driver may lose focus and become fatigued [26]. In particular, non-vocal and slow tempo music has been used in studies to relax drivers and improve their performance by helping them focus [4, 17, 27].

2.2 Biofeedback
A number of techniques have been developed to help individuals self-regulate the impact of stress, including various forms of meditation, deep breathing and biofeedback [22]. These techniques can be effective, provided that the patient adheres to

the training regime. Recent studies have looked at the combination of these techniques with games and music to promote regular practice. As an example, Parnandi et al. [18] presented a relaxation game that adapts game difficulty based on the players' breathing rate, in this way motivating players to relax so they can improve their score on the game. Zwaag et al. [29] created an affective music player that learned the user's physiological response to various music genres then, at a later time, played the appropriate music to match the user's desired mood. Bergstrom et al. [1] compared three techniques for modulating the user's heart rate: pre-recorded music, sonification of heart-rate (i.e., auditory biofeedback), and an algorithmically-modulated musical signal conveying the user's heart rate; their results show that music biofeedback was as effective as auditory biofeedback, and both superior to just listening to music. Epstein et al. [7] developed an intervention that allowed hypertensive patients to listen to music only if their muscle tension was low, as measured with electromyography. Dijk and Weffers-Albu [32] developed a system to calm individuals by guiding their breathing rate via musical, haptic and visual cues. Reynolds et al. [21] showed that combining autogenic training phases and music is more effective at promoting calm meditative states that using each treatment in isolation. In a similar study, Robb et al. [23] showed that combining progressive muscle relaxation and music led to lower anxiety levels than practicing each technique separately. In recent work Wells et al. [33] showed that audio-based biofeedback helps musicians lower their anxiety during musical performances. Siwaik et al. [24] developed an interactive biofeedback system with audio and visual channels of feedback to regulate breathing rate and reduce motion based artifacts during 4D CT scans. Lee et al. [16] introduced a music playback system which modified music in real-time based on dancer's respiration rate. Finally, Harris et al. [11] developed a tool to modify music based on the user's respiration rate using audio layering and noise addition techniques.

In the context of driving, Edmonds et al. [6] showed that biofeedback training prior to driving has strong effect on driving performance. Other studies have looked at changes in human physiology [8] and detection of stress [12] during driving using physiological sensors. To the best of our knowledge, however, ours is the first study to present a biofeedback intervention during driving to reduce stress.

3 SYSTEM OVERVIEW

3.1 Music modification

Our intervention is illustrated in Figure 1(a). A chest strap measures the driver's respiration rate and sends it to an audio modification application, where it is compared against the target range in Figure 1(b). If the driver's respiration is below the target rate (8 breaths/min), the musical piece is played without applying any modification. However, if the driver's breathing exceeds the target rate, the audio modification application adds white noise to the musical piece according to the piece-wise linear function in Figure 1(b). At 12 breaths/min, the noise amplitude is 50% the average amplitude of the music track; at or above 20 breaths/min, noise and music have the same amplitude.

We chose the target breathing rate based on prior studies [31] showing that heart rate variability –a physiological indicator of relaxation, is maximized at breathing rates around 0.1Hz (6 breaths/min). Reaching this breathing rate requires familiarity with deep breathing practice, and for this reason we chose a slightly higher rate (8 breaths/min) to ensure our study participants would be able to achieve it yet enjoy the calming benefits of slow breathing.

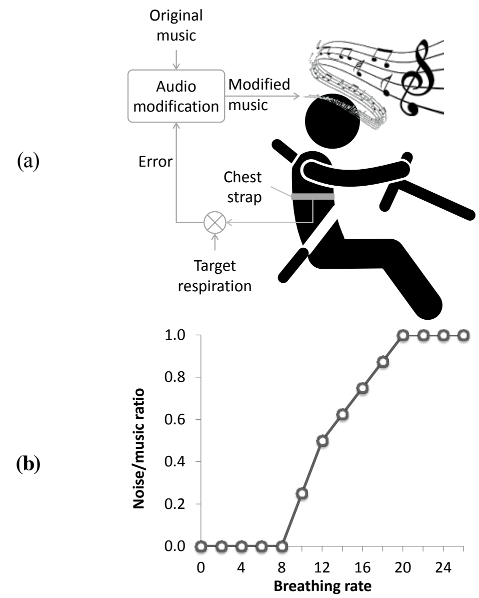

Figure 1. (a) Overview of our music biofeedback intervention. (b) Relationship between breathing rate and the ratio of noise amplitude to music amplitude

3.2 Tool interface

We implemented the audio modification tool as a mobile app on a Nexus 5 smartphone running Android 4.4 (KitKat). We measured breathing rate from a Bluetooth thoracic respiratory sensor (Bioharness BT, Zephyr Tech.) The mobile app allows users to select a particular song from their personal music library. Once a song is selected, the app modifies the audio according to the response curve in Figure 1(b).

3.3 Visual task

To simulate a visually-demanding task, we used an open-source car racing simulator, displayed on a 22" LCD and integrated with a racing wheel. To reduce variance across participants and experimental conditions, we modified the game so players were only required to steer the car, its speed at each position in the track being predetermined. The nominal speed profile for the track was obtained by recording game runs of a proficient player in a prior study [19].

3.4 Physiological arousal

We measured arousal with two well-known physiological indices: electrodermal activity (EDA) and heart rate variability (HRV). EDA consists of two components: a slow changing tonic skin conductance level (SCL) and phasic changes (spikes) known as skin conductance responses (SCRs) [2]. SCL are highly subject-dependent and measurement of baseline SCL is difficult in the presence of SCRs. For this reason we used SCRs as the EDA measure of arousal; following prior work, we computed SCRs using a peak detection algorithm over the complete dataset. We measured EDA using a FlexComp Infinity encoder (Thought Technology Ltd.) with disposable AgCl electrodes attached on the palmar region of the subject's non-dominant hand.

HRV is the physiological phenomenon of variation in beat-to-beat (R-R) intervals. We computed HRV as the root mean square of successive differences (RMSSD) in R-R intervals over a 30s window sliding by 1s [19]. We measured HRV with the same Bioharness BT chest strap from which we measure respiration rate. It is important to note that these two physiological measures were collected for monitoring purposes and were not used in any way for biofeedback purposes. When used in combination, EDA and HRV provide a robust index of arousal: changes in EDA and HRV are generally in opposite direction with increasing arousal (e.g. EDA increases while HRV decreases), so simultaneous increases (or decrements) in both variables can be dismissed as noise or motion artifacts.

4 EXPERIMENTS

We evaluated our intervention on a 2×2 study design with music and auditory biofeedback as independent effects; see Table 1. Participants (N=28; males: 82.15%; 22-35 years) were required to have prior driving experience. The protocol consisted of three phases, each lasting 5 minutes:

- Driving: participants played the car racing simulator to measure physiological baseline during driving
- Treatment: participants were randomly assigned one of the four conditions in Table 1 (n=7 participants per condition)
- Driving+treatment: participants repeated their assigned condition while driving the simulator

Participants in the MBF condition used the mobile app to practice deep breathing while listening to music during the treatment and treatment+driving phases. ABF participants used the mobile app similarly[1], except the music track was replaced with silence; thus, ABF participants heard white noise if their breathing rate was higher than the target, and silence otherwise. MUS participants listened to music without biofeedback, and control participants received no assistance (app or music). Music was delivered with stereo headphones, and the app's GUI was not visible during the experiment to avoid visual distractions from driving.

Table 1. 2×2 study design

	No Biofeedback	Biofeedback
No Music	Control (CTRL)	Auditory biofeedback (ABF)
Music	Music only (MUS)	Music biofeedback (MBF)

Prior to the experiments, participants in the MBF and MUS condition were asked to select two songs of the same composer from a predetermined music library; see Table 2. All songs had a slow tempo and were instrumental –such compositions have been associated with lowering physiological responses [5, 9, 20, 26]. Subjects also filled a questionnaire pre and post experiments for qualitative analysis. The study was approved by our Institutional Review Board.

Table 2. List of pre-selected musical compositions

Composer	Song 1	Song 2
Beethoven	Concerto No. 5	Fur Elise
Mozart	Andante	Andantino
Enya	Caribbean Blue	Watermark
Einaudi	Nuvole Bianche	I Giorni
Yo Yo Ma	Cello Suite No. 1	Meditation

5 RESULTS

5.1 Breathing

Figure 2(a) shows the average breathing rate for each of the four conditions at each stage in the protocol. Breathing rates for participants in the non-biofeedback conditions (CRTL, MUS) decreased moderately during treatment, but returned to the original levels during driving+treatment. In contrast, breathing rates for participants in the biofeedback conditions (ABF, MBF) dropped below the 8 bpm target during treatment and, more importantly, remained at that level during driving+treatment. 2-way ANOVA shows a main effect for biofeedback during treatment $(F(1,24) = 148.45,\ p < 0.05)$ and driving+treatment $(F(1,24) = 107.10,\ p < 0.05)$, but no music or interaction effects for either phase. Thus, both biofeedback interventions are effective at encouraging slow breathing during visually-demanding tasks.

5.2 Physiological arousal

Figure 2(b) shows the percent increase in HRV (relative to their levels during driving) for each of the four conditions. Participants in the non-biofeedback conditions showed similar HRV during treatment (or driving+treatment) than during driving, suggesting that music alone was unable to reduce arousal. In contrast, participants in the two biofeedback conditions had a large increase in HRV during treatment, and these levels were sustained during driving+treatment. As with breathing, 2 way ANOVA shows a main effect in HRV for biofeedback during treatment $(F(1,24) = 15.85,\ p < 0.05)$ and driving+treatment $(F(1,24) = 10.75,\ p < 0.05)$, but no music or interaction effects for either phase.

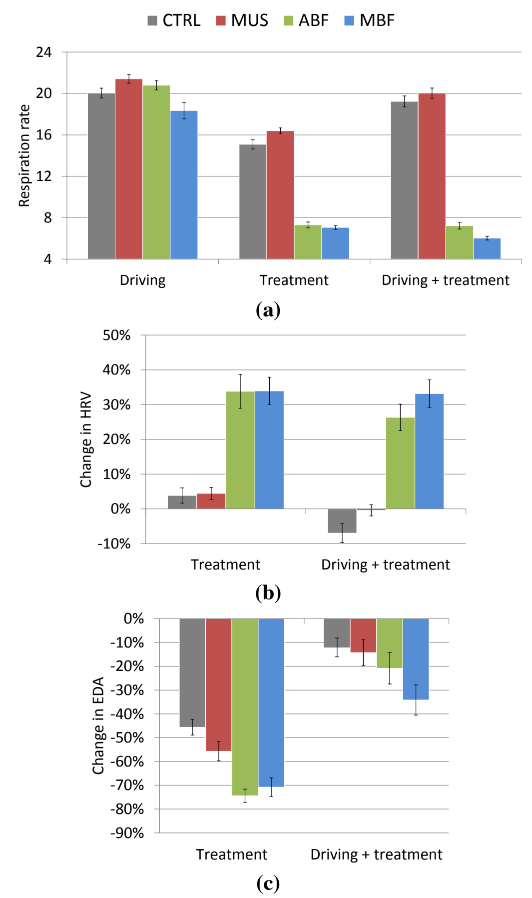

Figure 2. Physiological response. (a) Average respiration rate (across participants) during driving, treatment, and driving+treatment. Error bars indicate standard deviation. (b) Percent change in HRV (high HRV indicates relaxation). (c) Percent change in EDA (low EDA indicates relaxation).

[1] In both biofeedback cases (MBF, ABF) the level of noise guides participants towards reducing their breathing rate.

Figure 2(c) shows the percent reduction in EDA (relative to its level during driving). Participants in the four conditions (but particularly those under biofeedback) showed a large reduction in EDA during treatment, which suggests that the four conditions were effective in reducing arousal. Arousal levels during driving+treatment return close to their values during driving for all conditions except for MBF, which still shows a large (35%) reduction in EDA. This result suggests that music biofeedback is more effective than auditory biofeedback at lowering arousal during visually-demanding tasks. 2-way ANOVA shows a main effect in EDA for biofeedback during treatment ($F(1,24) = 4.20,\ p < 0.05$), a weak effect for biofeedback during driving+treatment ($p = 0.34$) and no music or interaction effects for either phase.

5.3 Subjective results

We also obtained subjective assessment for qualitative analysis of our results. When asked "*how negative (unhappy) or positive (happy) do you feel after listening to the music?*" on a 5-point likert scale (1: unhappy; 5: happy) participants in the two music interventions (MBF, MUS) reported being happier after listening to music during driving+treatment relative to only driving, while participants in the non-music interventions (ABF; CTRL) reported a decrease in their happiness level; see Figure 3(a). A 2-way ANOVA shows a main effect in valence (happiness) for music during driving+treatment ($F(1,24) = 6.17,\ p < 0.05$), but no biofeedback or interaction effects. Though participants in the four conditions reported a (subjective) reduction in arousal level, the reported reduction was largest for those in the MBF condition; see Figure 3(b). This result suggests that music biofeedback is more effective at lowering arousal during visually demanding tasks than music or auditory feedback alone.

When asked "*do you feel the music helped you reach a calmer state?*" the average rating for MBF and MUS participants was 3.4 (1: not at all; 5: extremely). Similarly, when asked "*how much did you like or dislike the songs?*" MBF and MUS participants provided an average rating of 4.57 (1: strongly dislike; 5: strongly like). We also found significant differences between ABF and MBF in terms of usability ratings: when asked "*would you use this app if it were available to you?" all MBF* participants responded in the positive, compared to three out of 7 among ABF participants. When asked *how often would you use the app?* The average answer for MBF and ABF participants was 3.28 and 2.42, respectively (1: not at all; 2: weekly; 3: several times/week; 4: daily; 5: several times/day). Finally, when asked "*how often were you able to listen to the music without any noise?*" MBF participants felt they were in better control over the quality of music and listened to the music devoid of noise more often than ABF participants (MBF: 3.71; ABF: 2.57) (1: never; 2: seldom; 3: about half the time; 4: usually; 5: always).

6 DISCUSSION

We have presented a tool for practicing relaxation exercises during visually-demanding tasks. The tool allows the user to listen to their favorite music, and adapts it to encourage slow, deep breathing. We compared this music-biofeedback tool against auditory biofeedback, music and a control condition, with three physiological measures as dependent variables on a car-racing simulation. When compared to the two non-biofeedback conditions, music biofeedback lead to lower arousal levels across the three physiological measures. While music biofeedback and auditory biofeedback were comparable in terms of respiration and HRV, music biofeedback did lead to lower EDA levels (i.e., lower arousal) than auditory biofeedback. The latter is a stronger result given that EDA is a more robust measure of arousal than HRV – HRV is modulated by respiration rate, whereas EDA is not.

(a)

(b)

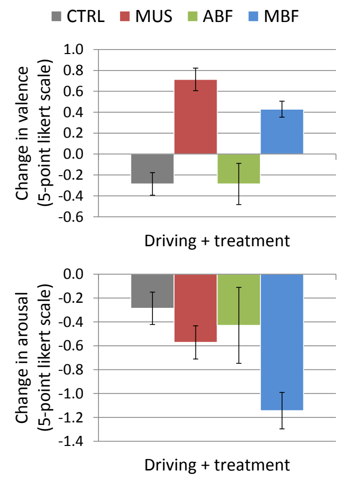

Figure 3. Subjective ratings. (a) Change in valence, measured using a 5-point Likert scale (1:unhappy; 5:happy). Error bars indicate standard deviation. (b) Change in arousal (1:calm; 5:excited)

Results from subjective ratings also indicate that music biofeedback leads to a larger reduction of arousal. Interestingly, the subjective reduction in arousal reported by subjects and percentage change in EDA –Figure 2(c) and Figure 3(b), respectively, are consistent with each other, supporting our argument that EDA is a relevant index of arousal. In terms of usability, the music biofeedback tool was preferred over auditory biofeedback tool. This suggests that music biofeedback is a viable stress-management intervention during driving and other visually-demanding tasks.

6.1 FUTURE WORK

Our study used slow-tempo instrumental songs, a music style that has been associated with reductions in physiological responses and better driving [17, 26, 27]. While our tool may in principle be used with any song in the user's personal library, additional work is needed to determine if the beneficial effects of music biofeedback hold when other music genres are used, particularly those that are designed to excite/arouse the user. The present study used additive white noise but more elaborate manipulations may also be investigated, such adapting musical properties (e.g. tempo) [16] or audio layering with multi-track recordings [11]. Further work is also needed to measure potential interference effects on driving performance and mental workload [4].

Our results are based on a modest sample size of college students (N>28), so further work is also needed to test the intervention on different demographics, particularly older adults and novice vs. experienced drivers. Further studies will also require more realistic and complex driving tasks (e.g., urban driving, unexpected events) than those possible with our car racing simulator, and measures of driving performance such as collisions or lane tracing accuracy.

For this study we used a sensor chest strap, but less cumbersome respiratory measurements are also possible. As an example, respiration rates can be measured with contact-free sensors (e.g., Doppler ultrasound) or estimated from webcams or smartphone cameras. In driving scenarios, respiratory sensors could also be integrated on car seats, and the music adaptation implemented on the car audio system.

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