Using Breath-like Cues for Guided Breathing

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ABSTRACT

Breathing exercises reduce stress and anxiety and are commonly implemented in well-being applications. Here, we compare how well three synthetic auditory feedback stimuli (breath, music, and compound) can guide slow and fast breathing. The results indicate that all three feedback types helped participants entrain the target breathing rate, however, the deviation from the target rate was higher for fast compared to slow breathing. Importantly, when target rate was fast, the compound feedback type resulted in a significantly smaller average respiration error and a longer duration close to the target respiration rate and the breath feedback type resulted in a smaller average deviation from target pace compared to music feedback type. The results point towards an advantage of compound and ecological sound stimuli in particular when the target respiration rate is fast.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; **Sound-based input / output**; Auditory feedback.

KEYWORDS

auditory/sonic feedback, respiration control, stress management

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1 INTRODUCTION

Breathing biofeedback is becoming an important part of e-health [33] as it helps regulate stress levels [14, 19, 30, 46]. Regulating stress improves physical and mental health [44] and the quality of life of users facing high-stress situations. Applications take several forms such as: adaptive biofeedback games [28, 41], commercial applications (e.g., Inner Balance, emWave2, myBreath, Pranayama), tangible interfaces [6, 7, 49], or virtual reality and artistic interventions e.g. [32, 34, 36, 47]. Promising results have been obtained with convenience users, veterans with post-traumatic stress disorder [31, 45], drivers [3, 27, 51] with children [41, 42], musicians, school and college students [9], athletes [22], and other user groups [14, 23].

Applications may employ an open and/or a closed loop. Open-loop applications provide visual, auditory, or tactile feedback cues using which users can adjust to a given respiration pattern. Closed loop applications communicate the state of measured psychophysiological parameters which users use to regulate their behaviour so that parameters remain within a target range. The considerable interest in breathing biofeedback applications makes feedback design research interesting and timely. We contribute by introducing and evaluating the use synthesized breath-like sounds for guided breathing in open-loop applications. This is a first step towards a more systematic investigation in using ecological stimuli for designing breathing biofeedback.

2 BACKGROUND

Most breathing biofeedback systems operate based on a closed loop. Physiological markers such as respiration rate, heart beat, or heart rate variability (HRV), or their derivatives are typically displayed. Most often visual feedback is used [14] and values are simply shown or plotted on the screen [14, 49]. More recent work uses respiration rate to control the composition of complex graphical representations.

Respiration has been used to control a visual animation of a game character as part of respiration-controlled games such as Chill-out [28] or ChillFish [41, 42]. Respiration control is also common in VR, starting from [8]. In Sonic Cradle [47], participants use respiration to regulate a synthetic soundscape while Solar [32] augments the experience with visuals. In Life Tree [29], respiration controls the growth and liveliness of a tree, while HRV has been used to control parameters of a virtual beach [36]. 'Social' biofeedback applications include Jel [43], in which participant respiration rate synchronicity controls growth and luminescence of a coral structure and soundtrack loudness or Breeze [10], a wearable pendant that presents the respiration rate of remote person using multimodal feedback. In [11], respiration rate controls remote tangible avatars and in [15] a remote digital photo frame surface.

Auditory biofeedback in closed-loop applications may simply consist of a continuous fixed timbre tone, whose frequency and/or

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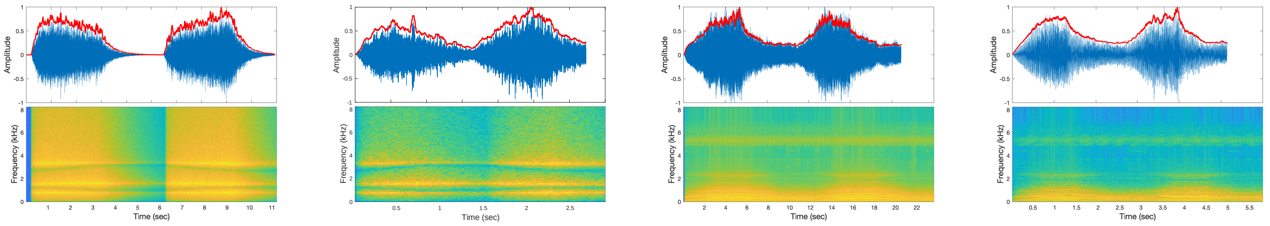


(a) (b) (c) (d)

Figure 1: The breath 5 BPM (a), breath 20 BPM (b), music 5 BPM (c), and music 20 BPM (d) stimuli used in the experiment. The time-domain signal and its envelope is shown above and the spectrogram below.

amplitude are mapped to a physiological measure e.g., heart-beat. Sound may also be used to present the deviation from a target parameter value by mixing white noise into a piece of music [5] or by reducing the number of channels [13]. Sound has been found effective at prompting users to reduce respiration rates while performing a secondary task.

Musical biofeedback is also common. Heart rate has been used to adjust musical parameters in [1, 2, 18, 25, 48] while [4, 38] mapped psychophysiological values to algorithmic composition parameters. UnWind [50] used natural sounds alone or in combination with music. Recently, there has been significant interest in haptic biofeedback [6, 7, 26] with applications providing tactile stimulation in synchrony with real or target heart rate.

Open-Loop Feedback: The implementation of closed-loop applications is not always straightforward as the acquisition of physiological data increases system complexity, may interfere with user activities, and poses privacy concerns. Furthermore, relating performance to a quantitative error metric can be misleading when it comes to breathing regulation techniques that typically originate in traditions and philosophies with different goals and value systems. Open-loop applications are less vulnerable to the aforementioned problems.

Visual open-loop feedback for guiding respiration may be binary such as a light that switches between inhalation and exhalation states or a continuous animation, such as an opening and closing circle [16, 31, 40]. Peripheral feedback has also been investigated [21]. Authors modulated screen brightness, used screen- or menu-bar dimming, or an animated semi-transparent horizontal bar moving up and down the lower third of a screen and found that they can be effective in helping participants to reduce respiration rate. A tactile open-loop system was presented in [3, 27]. A transducer array was placed at the driver's seat and signaled users to increase or decrease respiration. [20] investigate placement and signal types for tactile sensors for guided breathing.

This paper focuses on auditory open-loop feedback design. Auditory feedback is important as similar to tactile it does not require visual attention and interferes less with common visual tasks. Speech, non-speed, and musical sounds have been used. A metronome or simple tones can communicate inhale and exhale onset in a binary way [39]. Drivers receiving voice instructions [27] were also successful in reducing respiration rate by 28% on average and sustained this effect. A musical example is the use of two different harmonic chords modulated with the shape of a Gaussian function (an F-major chord and a C-major) to signal inhalation and exhalation periods [51]. They were significantly more effective compared to a placebo and background noise amplitude modulation in reducing driver respiration rate so that it remained below 120% its normal value. The amplitude of a musical signal was modulated in real-time according to a target respiration rate in [17], who compared a fixed (6 bpm) tempo, a personalized tempo (75% normal respiration rate) and a personalized envelope modulation. All designs slowed down respiration rate with the personalized tempo having the most marked effect. Physiological measures showed that users shifted towards a more calm state. Sound is also used in multimodal open-loop feedback as in the multimodal audio, visual, and haptic stimuli created for presenting respiration signals of others [10, 37]. Pink noise was used whose amplitude was modulated using a logarithmic scale. Exposure to the system affected the respiration rate of participants. Brightbeat [12] appears each time the respiration rate exceeds the desired one and causes display brightness and amplitude of white noise to oscillate (beat) according to the target respiration rate. The intervention also increased significantly the amount of time participants reached the goal respiration rate (10 BPM) to about 55% while performing other tasks.

Summary and Research Questions: Sound has often been used in open-loop breathing biofeedback applications. This may be binary, such as a tone or a voice instruction signaling inhale and exhale phases, or continuous in which case the amplitude of a musical or a noise signal is modulated according to the target respiration rate. Such feedback can effectively cue participants to shift their respiration rate towards a target one which benefits their psycho-physiological state. However, «the most obvious audio feedback is to record a person's breath», which is not used because «this would be complex to freely manipulate and render» [10]. Importantly, breathing along recorded breathing sounds resulted in reduced breath duration variability compared to synthesized musical sounds which implies that «ecological sounds captured the timing of breathing better than artificial sounds» [24].

Synthesized breath sounds may help overcome the difficulties in manipulating recordings and provide the malleable breath stimulus required for feedback design. Our research question is therefore whether a synthesized pseudo-breath sound signal can be used effectively to guide breathing towards a given respiration rate. As synthesized sounds do not contain all original signals details, their

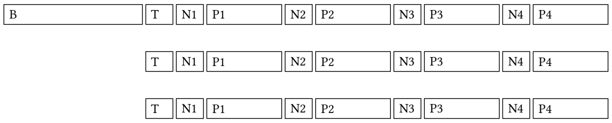


Figure 2: Setup of test sessions. Each testing phase is represented by a row in the figure. Stimulus was the same in each phase. B is baseline measurement (240s), T is training (30s), N1-N4 are normal breathing intervals (30s), and P1-P4 paced breathing intervals (120s). Paced breathing intervals were paired by respiration rate. A high respiration rate in P1-P2 was followed by a low respiration rate in P3-P4 and vice-verca.

efficacy needs to be tested. Our hypothesis is therefore that synthesized breath will work at least as well as the abstract musical and non-musical stimuli that are typically used.

3 METHOD

We evaluate our hypothesis in a controlled study that compares how well three auditory feedback types (a synthetic breath stimulus, a musical stimulus, and a compound breath plus musical stimulus) that encode cues to a target respiration pattern can guide participants into breathing along two (fast and slow) target respiration rates. The two respiration rates reflect relaxation and agitation use cases in the literature. The compound stimulus was introduced because the sound of breath played through headphones may sound uncanny and less preferred than music. A compound signal, if effective, may help combine the best of both worlds. In summary, the independent variables were: feedback type (respiration, music, and compound) and respiration pace (slow - 5BPM and fast - 20BPM). There were two repetitions for each combination. The dependent variables were the minimum and average deviation from the target respiration rate and the duration participants remained close to it.

Stimuli: The synthetic breath stimulus was modeled based on a female breath recording and was composed using a subtractive synthesizer. The recording was spectrally analyzed and formant frequencies for inhale and exhale phases were determined. Using the peaks, a formant synthesis technique was used which cross-faded between two sets of formant frequencies: 800.4, 1520.7, and 3281.4 Hz at amplitudes 1.0, 0.771, 0.996 and 747.5, 1588.6, and 3363.2 Hz at amplitudes 1.0, 0.4, 0.12. These were implemented using second-order band-pass Butterworth filters with a bandwidth of 100.3 Hz. The music stimulus was composed of discrete notes rising and falling in pitch. Discrete notes were sequentially introduced at even intervals during the inhale and exhale respiration phases. Inhale had 3 notes ascending, exhale has 3 notes descending. The third note of inhale was randomly chosen between two options. The compound stimulus was composed by combining the breath and music stimulus. Stimuli were prepared for both slow (5 breaths per minute) and fast (20 breaths per minute) respiration paces.

Participants: A total of 10 healthy adults (μ = 33.9 years, σ=12.67 years, 5 male, 5 female) participated in the study. Subjects did not report any respiration problems. They provided informed consent and completed a demographic questionnaire before the experiment. Participation was voluntary and could be terminated at any time. Subjects were compensated for their time.

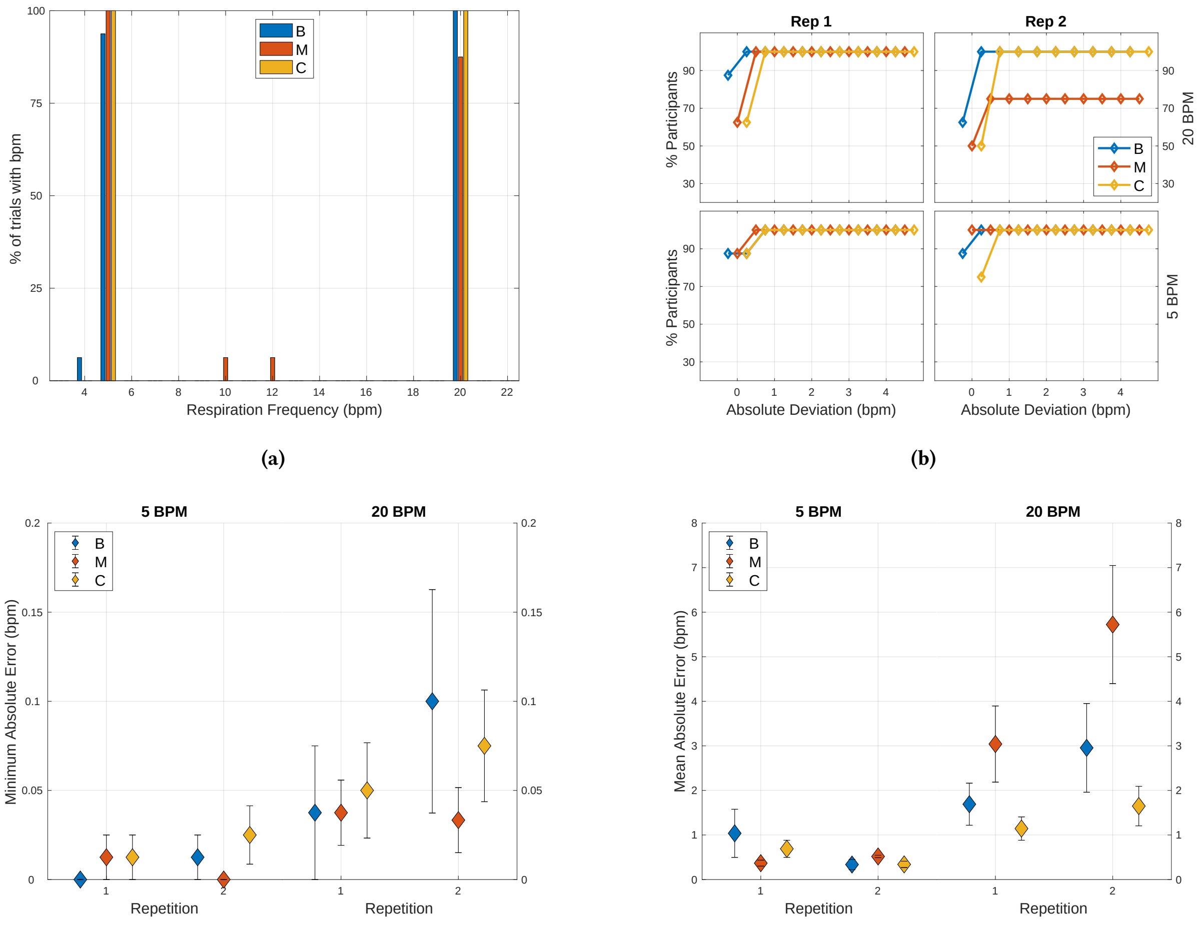
Procedure: Each experiment session started with a training phase in which participants watched a short instructional video presenting the sound stimuli, text instructions, and a video demonstration of a person breathing along the sound stimuli. The three testing phases that followed consisted of training (30s), normal (30s), and paced (120s) breathing sections (Figure 2). There was a baseline section (240s) in the first phase only to measure normal respiration rate. A single stimulus type (breath, music, or compound) was presented in each phase and the order of stimulus type presentation was counterbalanced across participants. Then slow, fast, and regular (non-paced) breathing sections were interleaved as illustrated in Figure 2. Notice that each respiration rate was tested twice before it switched in the paced breathing trials.

Setup: The stimuli sequence was prepared and saved in a video file. In the beginning of section, text instructed participants what to do i.e., breath normally versus breath along with the sound stimulus. Each session lasted about 1 hour. A PC played stimuli and collected data, a Vernier Go Direct® Respiration Belt measured respiration rate, an Arduino provided data from a PPG sensor, and sound was played by Sony MDRZX110 Headphones. The experiment was performed in a quiet laboratory environment.

3.1 Results

The minimum absolute deviation from the target respiration rate achieved in the trial intervals was estimated first. For two participants, this was higher than 100% the slow target respiration rate and 50% the fast target respiration rate in 50% of the trials, while it was similar to the rest of the participant group in the rest of the trials. Apparently, these participants were not able to perform the task in its entirety and were treated as outliers. The rest of the participants were within 10% of the target BPM on their best trial interval in all conditions in the experiment. Figure 3a shows the frequency of trial intervals with a given respiration rate. The best (closest to the target) achieved respiration rate in each trial is used. We see that most participants breathed at a pace close or exactly at the target respiration rate at some point during each trial. In two trials, the achieved respiration pace takes intermediate values at around 10-12 BPM which do not correspond to either the fast or the slow pace but is close to a normal breathing rate. These two trials were excluded from the dataset. The percentage of participants that were able to achieve a specific absolute deviation in BPM from the target respiration rate is shown in Figure 3b. We see that in their best trials most of participants achieve an accuracy of about ±1 BPM relative to the target respiration rate.

The average minimum absolute deviation from target respiration pace in each trial is shown on Figure 3c. As most participants achieved the target respiration rate this is small. A within-subjects feedback type × target respiration rate × repetition ANOVA was carried out on the minimum absolute deviation from target respiration rate. The main effect of target respiration rate was significant F(1,7) = 9.50, p=0.01, as the minimum absolute deviation increased significantly from $\mu = 0.01$ to $\mu = 0.05$ BPM when target respiration rate increased. No other main effects or interactions were significant.



(a)

(b)

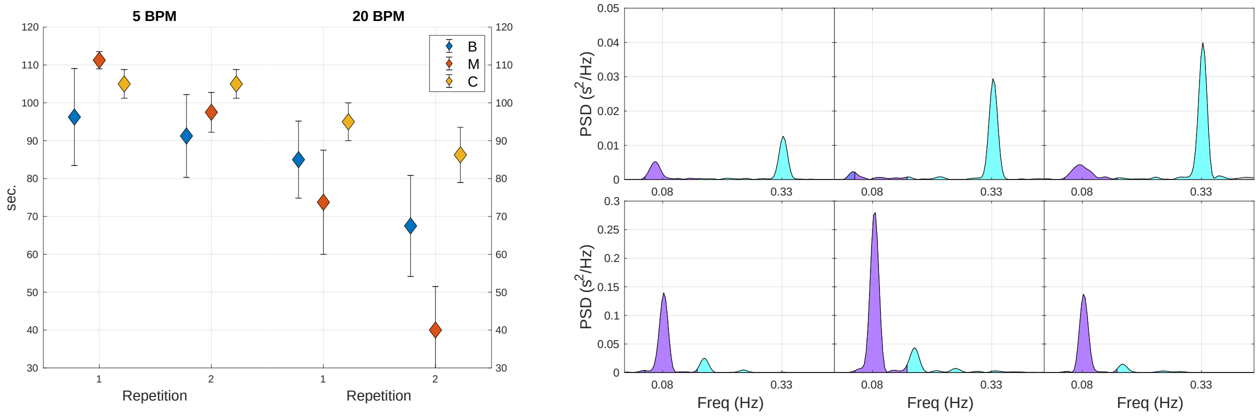
(c)

(d)

Figure 3: a. The percentage of trials achieving a given BPM. The best BPM during the trial is used. b. The percentage of participants that were able to achieve a specific absolute deviation (in bpm) from the target respiration rate. c. Average minimum absolute deviation from target respiration rate. Brackets indicate standard error. d. Average absolute deviation from target respiration rate. Brackets indicate standard error. [B: breath stimulus, M: music stimulus, C: compound stimulus]

Figure 3d shows the average absolute deviation from the target respiration rate. This increases when target respiration rate increases. A within-subjects feedback type × target respiration rate × repetition ANOVA was carried out on the minimum absolute deviation from target pace. The main effect of feedback type, F(2,14)=10.30, p=0.001, target respiration rate, F(2,14)=23.87, p=0.001, and repetition, F(1,7)=10.81, p=0.01, was significant. Minimum absolute deviation increased from an average of 0.54 BPM at the slow target respiration rate to an average of 2.7 BPM at the fast target respiration rate. The minimum absolute deviation also increased in the second repetition (1.91 BPM) relative to the first (1.33 BPM). The feedback type × target respiration rate interaction was significant F(2,14)=17.12, p<0.001. Post-hoc t-tests with Holm confidence interval adjustment showed that the interaction was significant because when target respiration rate was slow (5 BPM) the effect of feedback type on minimum absolute deviation was not significant. When target respiration rate was fast (20 BPM), minimum deviation was smallest for the compound feedback type ($\mu = 1.39$), significantly lower than both the musical feedback type ($\mu = 4.38$), p<0.001, and the breath feedback type ($\mu = 2.32$), p=0.05. Furthermore, the breath feedback type resulted in significantly lower absolute deviation than the music feedback type, p=0.01. The target respiration rate × repetition interaction was also significant, F(1,7)=13.64, p=0.007. The interaction was significant because the increase in minimum absolute deviation in the second repetition was not significant when target respiration rate was 5 BPM, but was significant when it was 20 BPM, p=0.011.

Finally, the duration during which participants maintained a respiration pace within 2 BPM of the target was calculated. This is plotted in Figure 4a. Remember that trial duration was 120 sec. Quite clearly, participants remain within 2 BPM of the target for most of the trial when target respiration rate was slow (5 BPM),



(a)

(b)

Figure 4: a. Duration within which participants stayed within 2 BPM of the target. Brackets indicate standard error. [B: breath stimulus, M: music stimulus, C: compound stimulus] b. Power spectral density of HR variation over illustrative fast (top panel) and slow (bottom panel) trials for the three feedback types used. Left panel is compound, middle is music, right is breath. Purple is low frequency and cyan high frequency spectral density.

however, this duration decreased when target respiration rate increased. Furthermore, a small deficiency can be observed for the music stimulus when pace is fast. A within-subjects stimulus × target respiration rate × repetition ANOVA was carried out with duration within 2 BPM of the target as a dependent variable. The effect of target respiration rate, F(1,7)=22.22, p=0.002, repetition, F(1,7)=12.82, p=0.008, and the feedback type × target respiration rate interaction, F(2,14)=6.16, p=0.012, were significant. The duration close to the target rate decreased from μ=100s to μ=70s when target respiration rate increased. The duration also decreased from μ=9.4s to μ=8.12s in the second repetition. Post-hoc t-tests with Holm confidence interval adjustment showed that the feedback type × target respiration rate interaction was significant because the effect of feedback type on duration was not significant when target respiration rate was low. When it was high, participants remained within 2 BPM significantly longer when feedback type was compound, in comparison to musical, p=0.009, while the rest of the differences between feedback types were not significant (p=0.09).

4 DISCUSSION

The goal of this study was to examine the efficacy of a pseudo-breath stimulus for guiding respiration in comparison to a musical stimulus at two target different respiration paces. The combination of pseudo-breath and musical stimulus was also examined. Efficacy was approximated by the accuracy with which participants followed the two target respiration rates as measured by three dependent variables: average deviation from target respiration rate, minimum deviation from target respiration rate, and the duration in which the measured respiration rate remained within 2BPM of the target.

Eight out of the ten participants were able to use the cues so as to adjust their respiration pace to the target one at some point during the trials. These participants also remained within 2BPM of the target respiration pace for 80% (slow pace) and 60% (fast pace) of the trial duration, respectively. This is comparable to the findings of similar studies in the literature e.g., 63% for a fast rate in [51]. Adapting respiration rate affected participants heart rate as found when analysing the pulseplethysmograph signal (PPG) using the HRVAS Matlab Toolbox [35]. Figure 4b plots the power spectral density of heart rate variation over selected trials for a selected participant. It can be seen that HRV peaks at frequencies expected given the target respiration paces, which points towards a relevant physiological state change. Overall, the results are supportive to the use of breath-like signals alone or in combination with musical ones to guide the respiration of users and enhance the design options that have been suggested by other studies in the literature [12, 17, 51].

A novel finding is that a fast respiration pace is harder to follow than a slow one. This is evidenced by the significantly higher average absolute deviation from target respiration rate, the significantly higher minimum absolute deviation from target respiration rate, and the shorter duration during which participants remained within 2BPM of the target respiration rate. Furthermore, the minimum absolute deviation from target respiration rate increased significantly in the second repetition relative to the first when the target respiration rate was high. The duration participants remained within 2 BPM of the target respiration rate also decreased in the second repetition. These findings may point to a difficulty in maintaining a target respiration rate over a prolonged period.

At the slow target respiration rate, all feedback types were equally successful in guiding respiration. However, auditory feedback affected the average deviation from target respiration rate and the duration within which participants remain within 2 BPM from the target respiration rate when target respiration rate was fast. The compound stimulus resulted in significantly longer duration within 2 BPM of target respiration rate and smaller average deviation from the target pace. Furthermore, the breath-like stimulus resulted in significantly smaller average absolute deviation from the target respiration rate in comparison to the music stimulus. While on average the breath-like stimulus leads to a longer duration close to the target respiration rate, the difference between breath and music feedback was not statistically significant. It appears therefore that the hypothesis that the pseudo-breath stimulus will work at least as well as the musical stimulus is verified and an advantage is registered for the fast respiration pace. Furthermore, the combination of pseudo-breath and musical stimuli seems to provide a further advantage at fast respiration paces. In informal discussion after the experiment, participants indicated a preference for the compound stimulus.

Two participants were not able to maintain the overall good performance standard in all trials and were treated as outliers and excluded from the analysis. This is somewhat puzzling as these two participants were close to the target respiration rate for about 50% of the trials and matched the target respiration rate during roughly one repetition for each of the feedback types and respiration speeds under consideration. Outlying measurements at 12-14 BPM, close to normal respiration rates, were also obtained at 2 out of the 96 trials for the rest of the participants (Figure 3a). Furthermore, a tendency for a performance deterioration in the second repetition was also observed in the statistical analysis. Taken together, these findings would imply that the most likely explanation for the outlying observations is that participants could not adapt to a target respiration pace over a longer period of time as required in the experiment. However, a difficulty in switching between fast and slow target respiration rates cannot be ruled out. Unfortunately, we are not able to give a concluding explanation and this issue needs to be investigated in a future study involving a larger participant group and a steady target pace within trials.

It appears that further research in the design and synthesis of breath-like stimuli is justified. Synthetic breath stimuli may improve the accuracy with which participants follow target respiration patterns because they contain valuable cues to the different respiration phases but also because they can help disambiguate musical cues when used in combination with them. Even with the simplified breath synthesis model we used in this study we were able to observe a significant benefit in feedback efficacy when target respiration rates increased. Future work could look into more detail into the synthesis of breath-like stimuli and examine how they can be combined with musical stimuli to achieve improved guided breathing experiences.

5 CONCLUSIONS

This study investigated whether synthesized breath-like cues can guide participants towards a target respiration rate as well as musical cues. To this end, we compared the accuracy with which participants could match either a fast or a slow target respiration rate using cues from synthesized breath-like or musical stimulus and their combination. The results indicate that all three feedback types helped participants approximate the target breathing pace. However, the deviation from the target respiration rate was higher for fast compared to slow breathing. Importantly, when target respiration rate was fast, the compound feedback type resulted in a significantly smaller average respiration error and a longer duration close to the target respiration rate. The breath-like stimulus also resulted in a smaller average deviation from target respiration rate compared to music feedback type. The results point towards a possible advantage for ecological sound stimuli and their combination with musical in particular at fast target respiration rates.

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