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Breath-Triggered Haptic and Acoustic Guides to Support Effortless Calm Breathing

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***Abstract*— Stress is a common issue in today's society and can be caused by a variety of triggers in activities such as work or driving. Various negative consequences can arise of stress such as reduced job productivity, sleep disorders, or physiological diseases like depression or anxiety. A popular approach to manage stress is voluntary deep and slow breathing. However, deliberate deep breathing requires conscious attention and effort, and thus often interferes with daily activities such as working and driving. We present a system that monitors the user's breathing in real-time and provides rhythmical feedback to support effortless and unconscious slow breathing in everyday-life. Our system comprises three feedback modes: 1.) acoustic feedback, 2.) haptic feedback, and 3.) mixed feedback combining both modalities. We apply our system in a driver setting and conduct a user study with twelve participants to evaluate the effects of our intervention on users' physiology and perception. We find that acoustic and mixed guiding can reduce breathing pace without affecting focus, which suggests that subtle rhythmical feedback is a promising approach to reduce breathing pace and thus counteract stress.**

I. INTRODUCTION

Stress can be elicited in various situations during everyday life such as work, during driving, or even from the virtual world [1]. Long-term stress can reduce job productivity [2], impair overall well-being, and can be associated with mental disorders such as depression, anxiety, and somnipathy [3], [4].

Due to these negative consequences, past research has explored approaches to manage stress and found that conscious and mindful breathing is an effective reliever of stress. In particular, it has been shown that voluntary slow and deep breathing induces calmness [5] and improves concentration, attention, memory, and eye-hand coordination [6]. However, everyday situations often do not allow pausing of an active task to consciously focus on breathing. Accordingly, approaches that require a minimum of attentional resources and still induce calm breathing are needed for real-life stress management applications.

Therefore, we propose to use subtle personalized rhythmical feedback using haptic and acoustic channels to effortlessly promote slow breathing. We develop a closed-loop system that monitors a user's breathing pace using a wearable device and triggers the rhythmical feedback just-in-time whenever needed. We apply and evaluate our system in a driver setting, which is one of the daily tasks that occupies a considerable amount of our time [7] and that does not allow to spend high attentional resources on a secondary task such as breathing. Further, driving itself is often associated with increased stress [8], [9] and both too high and too low stress have been shown to negatively impact focus and driving performance [10], [11]. Accordingly, an in-car intervention system that promotes slow breathing without decreasing attention on the road could potentially help to manage stress and thus contribute to road safety.

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II. RELATED WORK

In past research, breath modulation has been found to be an effective way to manage stress and to improve somatic, psychatric, and psychological symptoms and thus overall well-being [5], [6], [12]. Soni et al. [6] explored the effect of 10-minutes daily breathing exercises and found that controlled deep breathing can boost cognitive processes such as concentration, sustained attention, eye-hand coordination, and memory. Yogic breathing, according to Brown & Gerbarg [12], has been proven to counteract stress, anxiety, and depression on the one hand, while enhancing overall mood, mental focus, and attention on the other hand. Finally, based on a study with a duration of 8 weeks, Grossmann et al. [5] revealed that slow breathing can yield somatic benefits in the form of lowered blood pressure. Considering these effects as well as the fact that the physiological process of breathing, which is under autonomic control, can be regulated consciously opens unique opportunities for stress interventions [13].

Accordingly, there is already work approaching the development of breathing interventions. For instance, Prpa et al. [14] explored a breathing guide in an immersive VR environment with generative soundtracks and Schnädelbach et al. [15] built a responsive environment that reflects physiological signals to promote awareness and slower breathing. While these approaches highlight the great potential of breathing interventions, they all require conscious attention of the user which can be distracting when users are engaged in another task [16].

To make breathing interventions more applicable, there is also work considering more specific settings trying to make the interventions subtle and effortless for users. Ghandeharioun et al. [17] considered an office setting and evaluated rhythmical visual (brightness of the screen) and acoustic

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(white background noise) stimulation to induce slow breathing during a reading task. In their placebo-controlled study, they found a lower breathing rate as well as improved subjective calmness and focus in the condition with stimulation. Building upon this work, Leslie et al. [18] applied deliberately modulated ambient music during a sham task. The music was composed in real-time depending on the user's breathing behavior and influenced the breathing rate, electrodermal activity (EDA), heart rate, and slow cortical potentials measured in electrocardiographic signals, all consistently indicating a calmer user state.

Focusing on the domain of driving, Paredes et al. [19] explored different mindful in-car exercises to reduce stress including guided breathing in a simulator study. In follow-up studies, they investigated the potential of a haptic fast-paced breathing guide to increase driver's arousal [20] as well as a slow-paced breathing guide to calm the driver [21]. For the slow guide, they considered haptic (forty-one linear resonant actuators integrated in a seat swiping up and down) and acoustic (coach-like human voice that sets the breathing rhythm) feedback, both obviously presented to the user for conscious perception. The studies successfully demonstrate that it is feasible to influence the drivers' arousal state. However, their findings also indicate that consciously following the breathing guide is not a suitable solution for demanding driving settings. Balters et al. [22] brought the haptic intervention into a real car and evaluated the intervention on a closed-circuit track. Their results show successful breathing pace reduction, but some participants' feedback revealed that low arousal states can be intensified by the intervention. Finally, Zepf et al. [23] focused on the impact of the awareness of acoustic interventions on efficacy and driving performance. The results of their simulator study showed that a conscious intervention reduces breathing but also increases the number of driving mistakes. The participants of their study noted that more subtle interventions are more appropriate for a driving scenario.

In this work, we describe an intervention system using subtle haptic and acoustic breathing guides as well as a combination of both aiming to safe and balance attentional resources and increase the intervention efficacy. The closed-loop system monitors the users breathing rate to trigger interventions just-in-time whenever users are breathing too fast and personalizes the intervention depending on the users individual breathing behavior. We apply our system in a real car and present the findings from our evaluation study.

III. Breathing Guides

A. Acoustic Intervention

The acoustic intervention is intended to be applied through any type of audio speaker. For the intervention design, we first gathered feedback from six volunteers to find a song that serves as a basis for our intervention. We asked the volunteers to report which song out of a list of five pre-selected songs s/he finds most convenient for a car journey and asked them to rate the songs in terms of valence on a 7-point Likert-scale. Based on the feedback, we selected an ambient music mix from YouTube, which was selected most often and was rated neutral in terms of valence [1]. Subsequently, we presented the selected song with different ranges of volume modulation and two different modulation functions (sine and pyramid) to the volunteers, asking them to choose the most relaxing setting and to rate how clearly they perceive the modulation. The participants' reported higher perceived relaxation for the sine pattern and suggested that modulation becomes noticeable from 60% to 100% of the volume. Accordingly, we adopted these settings for the acoustic intervention.

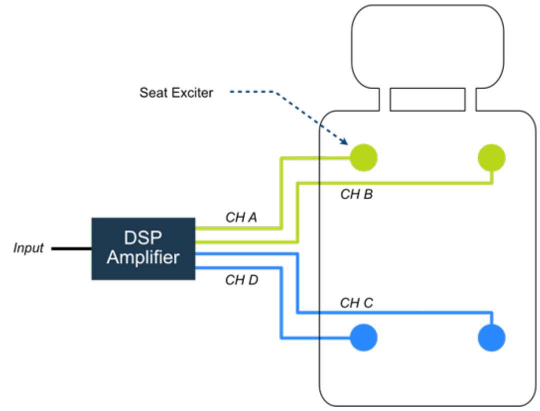

Fig. 1. Technical overview of the haptic intervention.

B. Haptic Intervention

The setup for the haptic intervention is based on four vibration elements that are integrated into the driver's seat. As presented in figure 1, two vibration modules are located at the height of the lower back and two are placed next to the approximate position of the bladebones. Two amplifiers that can be actuated by a tone generator are used to allow separate triggering of the upper and the lower vibration modules. Similarly as for acoustic, we conducted pilot testing to find a suitable basic tone frequency that triggers comfortable vibration. Based on the feedback, we decided to apply a default tone frequency of 45Hz. In comparison to the acoustic intervention, the haptic intervention allows to manipulate an additional parameter: the upper and lower vibration elements can be triggered separately, which allows to introduce a phase shift between these two actuators to stimulate the user with different patterns. We presented both a version without and with 50% phase shift to participants. Since participants reported that the phase shift creates a pattern on the back that is similar to breathing, we decided to apply the variant with phase shift. Subsequently, the volunteers experienced different ranges of intensity modulation and two different modulation functions (sine and pyramid). For the intensity range, people reported that 40% to 100% of the intensity is close to the perception limit and still drowns the car noise. Regarding the modulation function, the reports did not give a clear indication on any preference, so we applied the same function as for the acoustic intervention, namely sine.

[1]https://www.youtube.com/watch?v=n0svuurLibQt=1284s

Fig. 2. BioModule bio-sensor from Zephyr with chest strap.

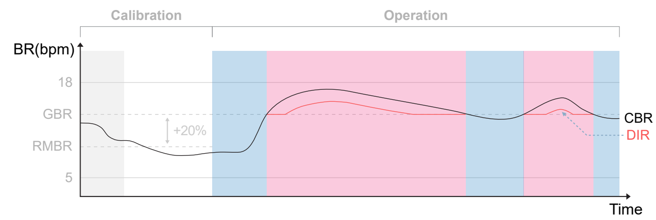

Fig. 3. Exemplary development of CBR (black line) and DIR (red line) with the background colors indicating the calibration process (grey for discarded data, white for considered data), sequences with activated intervention (red), and sequences with deactivated intervention (blue).

C. Closing the loop

Building upon the two previously described interventions, we designed a closed-loop system that measures the user's breathing rate and activates an intervention whenever the user's breathing rate exceeds a personalized threshold.

To capture biosignals, we used Zephyr's BioModule sensor attached to the user's chest with its respective strap (see figure 2). This sensor measures the users breathing rate, which is used as a trigger for the system, as well as heart rate and its variability, which is later used for additional analysis.

For a personalized activation threshold, the system requires a calibration to obtain the individual mean breathing rate during rest. Therefore, three minutes breathing recording during relaxation is necessary to calculate the mean resting breathing rate (MRBR). Assuming that the user needs some time to arrive in a relaxed state, the data of the first minute is discarded and the data of the second and the third minute is used to compute the MRBR. Based on previous approaches, the personalized goal breathing rate (GBR) is defined as 120% of the MRBR with lower and upper bounds of 5 and 18 breaths per minute [17], [23]. In contrast to Zepf et al. [23], the upper bound was increased by three breaths per minute, since the MRBR distribution of their study indicated that most participants reached the upper bound.

During operation of the intervention system, the current breathing rate (CBR) is continuously compared against the GBR, and an intervention is activated whenever the CBR exceeds the GBR. When activated, the system applies a dynamic intervention rate (DIR) which means that the intervention modulation frequency is continuously updated to be two breaths per minute slower than the CBR. The goal of the DIR is to improve the engagement and "lead" the user gently back to GBR. Since no lower CBR is desired, the minimum modulation frequency is the GBR. As soon as the CBR is equal to or falls below the GBR, the intervention is deactivated. Figure 3 illustrates an exemplary CBR development and the resulting system behavior. The system allows to select between three modes: 1.) acoustic intervention only, 2.) haptic intervention only, and 3.) mixed mode in which both interventions are applied simultaneously.

IV. User Study

A. Experiment Design

The user study was designed as a within-subjects experiment consisting of four conditions that are all presented to each participant in randomized order. The conditions are the same as the modes of our prototype, namely acoustic, haptic and mixed as well as a neutral condition without any intervention for comparison. The randomization is based on a Latin Square.

To minimize safety concerns, the study was conducted on the institution campus. While this avoids involving public traffic, the campus represents a realistic driving environment, including other vehicles and typical road scenarios such as crossings and crosswalks. The length of the selected route was 3,75 km and takes around 10 minutes. To assess the perception of users in each condition, we prepared a 6-item questionnaire that was given to participants after each drive. The questionnaire requested ratings for pleasantness, energy, stress and focus each on a 7-point Likert-scale and included two yes/no questions asking whether any haptic or acoustic feedback was perceived by the participant. For each positive answer, an additional question appeared asking to rate how calming the respective type of feedback was perceived on a 7-point Likert scale.

The study vehicle was a Mercedes-Benz S-Class. The seat exciters were integrated into the drivers' seat as explained in section III-B. A laptop was used to run the software of the intervention system and an interface was implemented that allows to connect to the amplifiers of the seat exciters and the in-car speakers via USB. After starting the system manually, the laptop can be placed in the foot area of the co-driver and participants can take an unaccompanied drive.

B. Procedure & Participants

At the beginning of the study, participant were given a general overview of the upcoming procedure via an audio sample. After voluntarily signing the consent form, they were equipped with the BioZephyr sensor. Subsequently, an introduction to the car and its functionality was given. The volunteers were informed that there might be rhythmical feedback during the study to avoid the risk of suprises without giving them more information about the interventions and the purpose of the study. All participants were familiar with the campus and the destination of the route. After clarifying remaining questions, the calibration was accomplished. To do so, participants were told to sit still in the car and try to relax for three minutes. For the main study, participants drove the route four times to experience each condition with a quick stop in between each to give ratings. After all drives, the final questionnaire was answered, the bio-sensor was removed and the procedure completed. Overall, twelve people participated in the study with an age ranging from 25 to 40 years ($\mu = 31.33$, $\sigma = 4.50$). The study involved seven male and five female participants with an average driving experience of 10.2 years.

V. Results

A. Biosignals

For the analysis, we pre-processed the biosignals, namely the *breathing rate*, the *heart rate*, and the *heart rate variability* by computing the mean of each participant and each drive to be able to conduct comparisons between the different conditions. Additionally, we adopted the normalization method from Leslie et al. [18] and applied the z-score on the resulting mean values for each participant and signal. This was done to account for personal differences and to highlight potential relative differences between the conditions.

After the pre-processing, we conducted the Shapiro Wilks test to select appropriate statistical tests for the comparisons. For all biosignals, the data was normally distributed and thus parametric tests are selected, namely ANOVA and the t-test for post-hoc analysis.

To evaluate the effect of our interventions on physiology, we compared the mean values of each signal between our study conditions over all participants. Table I provides an overview of the p-values of the statistical tests.

Comparing the four conditions based on the ANOVA test, we found a significant difference ($p = 0.006$) of the breathing rate, which was the main objective of this study. A pairwise post-hoc analysis based on t-test with Bonferroni correction revealed significant differences between the acoustic intervention condition and the baseline ($p = 0.027$) as well as between the mixed intervention and the baseline ($p = 0.032$). All other pairwise comparisons showed no significant differences (all $p > 0.05$). These findings indicate that the acoustic and the mixed interventions successfully reduced the participants breathing rate. However, the fact that there are no significant differences between the mixed and the acoustic intervention as well as between the haptic intervention and the baseline suggests that the haptic intervention is not effective in slowing down the breathing pace. The left graph of figure 4 illustrates boxplots of the mean breathing rate over all participants for each condition.

Additionally, figure 4 shows the mean heart rate (middle graph) and its variability (right graph) for each condition over all participants. For both signals, an ANOVA reveals no significant differences between the four conditions ($p = 0.973$ for heart rate and $p = 0.101$ for heart rate variability). While the medians of all conditions are very similar for the heart rate, the heart rate variablity boxplots show a tendency towards a higher median value in the condition of the acoustic intervention. Since increased heart rate variability is commonly associated with a relaxing state, this tendency could be a slight hint on improved calmness during the acoustic intervention. This should be further investigated with a higher sample size to clarify the relation of the heart rate variability and the interventions.

TABLE I

Statistical comparisons for the breathing rate, heart rate, and heart rate variability between conditions.

	HR	BR	HRV
	ANOVA		
all conditions	0.973	0.006	0.101
	T-test + Bonferroni Correction		
baseline vs. haptic	1	1	1
baseline vs. acoustic	1	0.027	0.313
baseline vs .mix	1	0.032	1
haptic vs. acoustic	1	0.390	0.279
haptic vs. mix	1	0.560	1
acoustic vs. mix	1	1	0.331

TABLE II

Mean and standard deviation for the subjective self-ratings under different conditions

	Energy	Focus	Pleasantness	Stress
acoustic	4.2±0.83	4.9±1.24	5.0±0.85	2.3±0.89
baseline	4.3±0.98	4.9±1.0	5.2±0.83	2.8±0.97
haptic	4.2±0.72	5.2±0.87	4.9±0.9	3.0±1.28
mix	4.2±1.06	4.8±0.97	4.8±0.94	2.6±1.16

B. Questionnaire Analysis

Apart from the biosignals, we analyzed the different ratings obtained by the participants to better understand their perception of the interventions.

Firstly, we examined the calmness ratings for the two interventions given directly after each drive in case they perceived feedback. When presented individually, the acoustic rating obtained a mean score of 4.5 (SD = 1.73 and the haptic version was rated with 3.8 (SD = 1.17) on a 7-point scale. This suggests and the participants perceived the acoustic feedback as more calming. Comparing the individual ratings with the ratings obtained in joint perception during the mixed interventions shows that the acoustic intervention is rated less calming when perceived along with the haptic feedback (Acoustic ratings during mixed: M = 3.6, SD = 1.14, haptic ratings during mixed: M = 3.6, SD = 1.43). This could indicate that experiencing the haptic feedback interferes with the perception of the acoustic feedback.

Additionally, we examined the users' ratings for the drives in terms of energy, focus, pleasantness and stress between the conditions. Table II provides an overview of the ratings. Overall, little variance between the conditions can be found. The largest differences are in the stress ratings, yielding a 0.5 points lower score for the acoustic condition than for the baseline, which could indicate a slightly higher relaxation for the acoustic intervention. However, an ANOVA reveals no significant differences between conditions for all factors. Regarding the focus, this suggests that the interventions did not impair the concentration of the participants, which supports that the goal of keeping the interventions subtle and appropriate for the demanding task of driving was fulfilled.

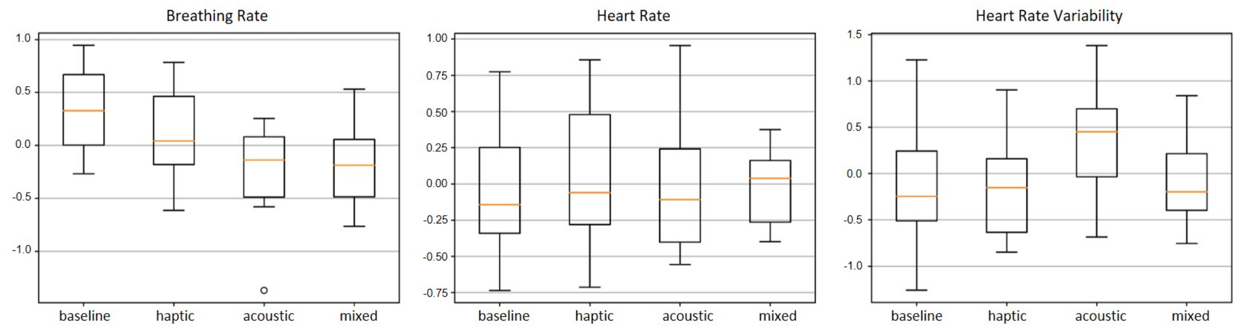

Fig. 4. Boxplots of the mean normalized breathing rate (left), heart rate (middle) and heart rate variability (right) for each condition.

VI. Conclusion

In this paper, we presented a closed-loop system that analyzes user's breathing to trigger rhythmic feedback supporting calm breathing and thus induce relaxation. The system comprises three types of interventions, namely acoustic feedback, haptic feedback, and mixed feedback combining both modalities. We integrated the system in a car and conducted a driving study with twelve participants to compare the intervention types and to evaluate their effects. We found that the acoustic and mixed intervention effectively reduce the breathing rate without affecting focus which indicates that they are a suitable approach for stress management in cars. Further, we believe that our intervention system can be transferred to other scenarios such as an office setting, integrating the vibration elements into the office chair and using the computer speakers. We look forward to a future, where automated breathing guides allow a more relaxing experience during everyday tasks.

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