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aSpire: Clippable, Mobile Pneumatic-Haptic Device for Breathing Rate Regulation via Personalizable Tactile Feedback

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Figure 1: (a) aSpire, a clippable pneumatic-tactile feedback device with 3 soft actuators. (b) Control UI that allows users to select/create different tactile patterns. (c) User test of aSpire on passengers in on-road commuting environment. aSpire clipped on; (d) a seat-belt for breathing guidance and providing comfort for vehicle passengers, (e) a back pack strap during walking.

ABSTRACT

We introduce–aSpire–a clippable, mobile pneumatic-haptic device designed to help users regulate their breathing rate via subtle tactile feedback. aSpire can be easily clipped to a strap/belt and used to personalize tactile stimulation patterns, intensity, and frequency via its array of air pouch actuators that inflate/deflate individually. To evaluate the effectiveness of aSpire's different tactile stimulation patterns in guiding the breathing rate of people on the move, out-of-lab environment, we conducted a user study with car passengers in a real-world commuting setting. The results show that engaging with the aSpire does not evoke extra mental stress, and helps the participants reduce their average breathing rate while keeping their perceived pleasantness and energy level high.

CCS CONCEPTS

• **Human-centered computing** → **Mobile devices**; **Haptic devices**; *User studies.*

KEYWORDS

Health, Haptics, Wearable, Affect Regulation, Respiration, Stress

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1 INTRODUCTION

Breathing exercise has health benefits such as enhancing heart rate variability, reducing mental stress, and promoting a generalized state of relaxation [8, 20, 33]. A growing number of studies in Human-computer Interaction (HCI) have developed and explored new interfaces to assist people in regaining and sustaining attention to their inner body through breathing [31], and to regulate negative affective state [27]. Despite making many advances, however, most of the devices lack mobility and a convenience that enables them to be deployed and tested in natural daily-life environments. Additionally, their studies have not examined pneumatic-tactile feedback for guiding breathing rate (BR) control.

To promote breathing exercises that are convenient to test in daily life without inducing extra mental stress, we introduce aSpire, a mobile tactile feedback device that guides users to control their BR. aSpire provides various tactile stimulation patterns enabled by an array of pneumatically-driven soft actuators. The mobile and clippable design allows users to wear aSpire around their body during daily routines. To evaluate the effectiveness of aSpire in guiding the BR in the wild, we conducted a user study in a real-world on-road commuting setting. In addition, we assess the passengers' acceptance and perception of two different rhythmic tactile stimulation patterns and discuss the findings from the results. Lastly, we address limitations of the current work and future work. This work suggests 3 main contributions: • **(1)** We explore a pneumatic-haptic system as an effective and engaging tactile guidance for regulating BR without inducing extra stress and introduce a clippable design which allows programmable "physical nudges" in new kinds of designs,

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such as straps. • **(2)** We introduce a compact and mobile pneumatic control system that individually controls the shape deformation of the soft actuator using a single pump, which enables the system to program various tactile patterns. • **(3)** We demonstrate aSpire's effectiveness on a seat-belt in lowering BR by conducting a user study in a real-world commuting setting. The findings suggest that it can help passengers achieve their goal BR without inducing extra stress, and expand the biofeedback design space with the arrayed pneumatic nudges.

2 RELATED WORK

Compared to 'tactile' devices for BR regulation [3, 27, 29, 30, 35], we designed aSpire to be mobile, comfortable, and personalizable in its nudge (pattern, goal BR, intensity) via its UI, which are important values to make it deployable during daily activities. Although [5] has a mobile cushion form, its form factor limits users to carry it around their bodies. While [3, 4, 30] explored vibrotactile feedback for regulating the drivers' BR, aSpire provides mobility and explores pneumatic pressure as a tactile nudge. We explored different nudge patterns' effect while few studies did. Commercial products [6, 34] do not give pneumatic nudges and require holding which limits the users' activity. Smartwatches are wearable, but they use vibrotactile cues and do not permit closed-loop intensity feedback control. Users tell us aSpire's nudges feel more natural and do not require attention, while Apple watch with Breathe App. [17], devices [10, 37] and meditation apps ask you to focus on their cues [23] or require a dedicated silent space to help users focus [11]. Watch-type wearable devices [2, 11, 13] are mobile but all of them were tested for regulating heart rate in-lab environment.

3 DESIGN RATIONALE AND REQUIREMENTS

Our goal is to develop a non-intrusive tactile feedback device that guides users to regulate their BR during daily activities without inducing extra mental stress. We focused on the tactile modality as opposed to other sensory modalities for influencing BR. Perceiving the guidance and information through the perception of touch is expected to be less-interrupting for users who are more likely to be occupied with their visual and auditory cognitive load while performing foreground tasks during their daily routine [30, 35, 36]. Paredes et al. [30] showed that drivers (of a car simulator) preferred the haptic over the voice-based guidance due to its less obtrusiveness. To achieve our goal, we have set the following design requirements: **(1) Personalizable:** The device should be able to provide users with ability of adjusting the tactile stimulation intensity and pattern to accommodate their different BR, preference and sensitivity. **(2) Comfortable:** The tactile stimulation from the device should not evoke any physical discomfort and mental stress; it should be close to organic with a non-machine-like comfortable feeling. **(3) Mobile:** The device should be able to be carried or worn on the users' body and its location on the body should be easily adjustable.

Balters et al. [3] recommended to provide an ability of varying the tactile patterns and intensity. Also, the effect of personalizing the feedback and letting the users to choose their preferred biofeedback method on their engagement level was shown by [27, 30]. Based on these findings, we considered the req.-(1). We took a metaphorical notion [26] of natural motions of the human lungs and chest. We believe that rendering a tactile stimulation inspired from the motions and feelings of the human's respiratory system could provide a familiar and comfortable feeling. This intuition led us to focus on developing pneumatic soft inflatables with clippable design (req.-(3))

4 IMPLEMENTATION

aSpire is clippable on a belt/strap such as seat-belt, waist-belt, cross-bag strap, etc, which can be easily found from daily items. This allows the device to be deployable during daily activities. We designed the tactile stimulation modules arrayed in a line to render various tactile patterns including directional information. aSpire consists of three soft actuator modules with embedded stretchable pressure sensors and a pneumatic control system module (Fig. 2(b)). To develop the device compact and implement the closed-loop control of the tactile stimulation intensity, we created a stretchable pressure sensor (Fig. 2(e)) that can be integrated as a part of the actuator material. We embedded the sensor system on the actuator membrane that responds to the volumetric deformation of the actuator by varying its resistance value. Based on the 5 solenoid valves' ON/OFF state and its ON/OFF duration, the system can control the deformation speed of the individual actuator using only a single motor. To support users to control the tactile intensity, goal BR, and to select tactile pattern, we developed a mobile UI using P5.js (Fig. 1(b)) to make it wirelessly accessible by any Bluetooth mobile device via web browser without requiring of app. installation. aSpire can deliver up to 15 bpm with various tactile patterns. The maximum acoustic noise level of aSpire was measured as 43 dB from the 1 cm distance (ambient noise was 24 dB). This noise level is relatively low given the noise in a restaurant/office is around 60 dB. No participants of the pilot and user study expressed distraction due to the noise during either the in-car/in-lab test. The maximum normal contact force that the actuator can handle was measured as 17.7N. The weight of the device is 252 g.

5 PILOT STUDY AND INSIGHTS: REAL-WORLD RIDING SETUP AND TEST-DRIVE

We emphasize that our study purpose was not to 'reduce stress' using aSpire, but to evaluate the efficacy of its subtle tactile nudges for regulating the BR of people on the move, out-of-lab environment without inducing stress. In the U.S, most people spend 43 - 53.2 min on average per day on the road to commute in a vehicle [24] and this represents the longest time people spend other than on indoor activities/sleeping [21]. This average commute time and the number of public transit ridership has kept growing [1, 9] as well as the anticipated autonomous car riding. Reflecting on this, we designed the study protocol in a real-world car commuting setting. Although driving is more stressful, passengers also experience stress and negative states [14, 32, 38]. Like [3, 4, 30], we plan to also test drivers' use, but since our pneumatic nudges are novel, to maximize safety we first tested passengers. We test-drove a sedan with 3 participants (3 males, mean age = 29.33, sd = 7.76) on a round-trip driving route in one of the most congested metropolitan areas in the U.S. The driving route was a two-lane road with a speed limit of 35 miles per hour and took 30 minutes of driving. We divided

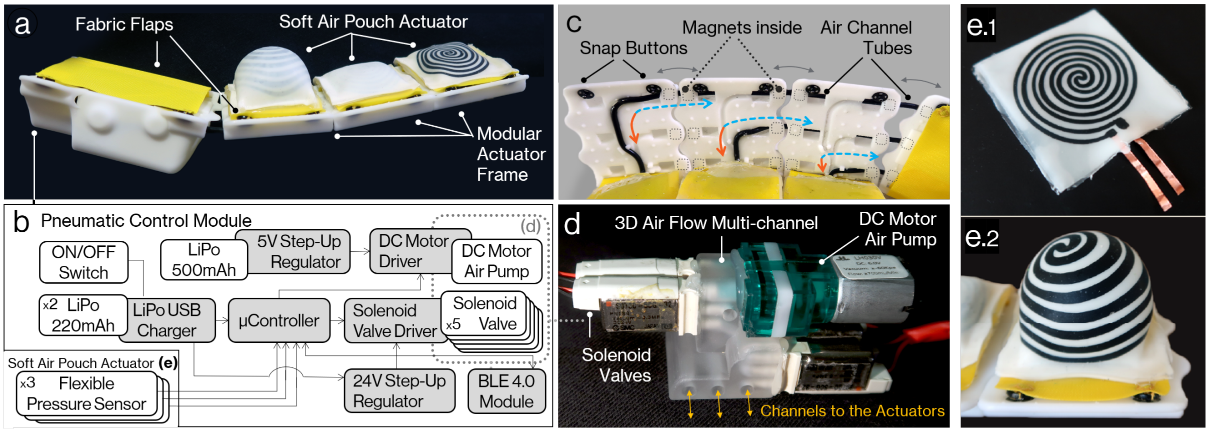

Figure 2: (a) Overview of aSpire (b) Electronic system diagram of pneumatic control module (c) Inner view of the aSpire when the clips open. (d) Hardware configuration of pneumatic control system using a 3D printed air flow multi-channel structure to increase space efficiency. (e.1) Stretchable pressure sensor. (e.2) The sensor integrated as a part of the actuator membrane.

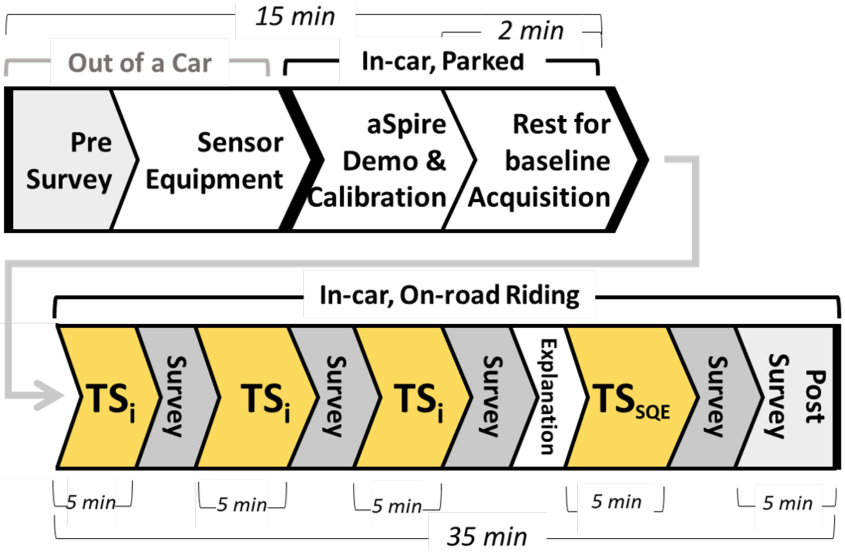

Figure 3: The user study procedure. TS$_i$: tactile stimulation mode in randomized order. $_{i=}$; $_N$: No stimulation (control condition), $_{SC}$: Synchronized mode, $_{SQ}$: Sequential mode, $_{SQE}$: Sequential mode after explanation of the device purpose

the route into 4 segments to test 4 different conditions of the aSpire operations for 5-min each. From the test-drive, we confirmed the driving route's safety and its typical commuting environment. We drove the route several times in different time span and set between 10 AM to 4 PM to avoid the extremely crowded traffic and keep the participants' study experiences consistent across duration, traffic, and driving speed.

We used the Zephyr BioHarness [18, 19], chest belt-type sensor, to collect the passengers' BR. When they were wearing the sensor and had the seat-belt fastened, they reported that the stimulation was too subtle compared to when they were not wearing the sensor. This was due to the tension of the sensor's belt applied to their chest area. Therefore, we had to increase the tactile stimulation intensity of the aSpire. This was easily changed thanks to the device's personalization ability. Also, when we clipped the aSpire on the lap-belt of the seat-belt, often it interfered with the sensor or a waist-belt that the participant already wore, and caused a discomfort, so we clipped the aSpire on the shoulder-belt, which also the most of participants preferred.

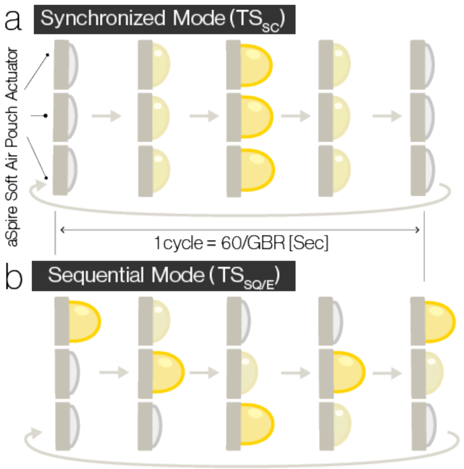

Figure 4: Two different tactile stimulation modes used in the user study

6 USER STUDY: ENGAGEMENT AND ACCEPTANCE OF ASPIRE IN REAL-WORLD RIDING SETTING

6.1 Objectives and Hypothesis

Our work aims to develop a device that offers subtle pneumatic-haptic feedback, and satisfies the design requirements. In addition, we want to explore its potential as an effective breathing guide easily used during daily activities. To evaluate the developed system, we set the following hypothesis: • **H.1.1**: For different tactile stimulations tested in a randomized controlled trial, aSpire will help car passengers lower their BR to reach a goal breathing rate. • **H.1.2**: The brief disclosure of the device's information will increase the engagement level in the aSpire's breathing guidance. • **H.2**: Engaging with the subtle tactile feedback from the aSpire while maintaining the same level of energy and pleasantness will not cause any extra mental stress of the passenger riding a on-road car. • **H.3**: Even without explaining how to engage with the tactile feedback to the participants, they will associate their inhalation and exhalation with the different actuator array motions, and there might be an association mostly selected.

6.2 Procedure

Fig. 3 shows the main user study procedure confirmed through the pilot study. The study protocol was approved by the Institutional Review Board. All participants were compensated after the study with a $25 check. They were asked to fill out the consent form, demographics survey, and Perceived Stress Scale (PSS) survey [12]. They were asked to wear two sensors, BioHarness and Q-sensor (Affectiva). The BioHarness was worn around the chest capturing the BR. The Q-sensor was for acquiring electrodermal activity (EDA) and worn at the wrist of non-dominant hand. As shown in the Fig. 1 (c, d), each participant sat in the rear car seat and fastened the seat-belt where the aSpire was attached. The experimenter demonstrated 3 different operation modes of the device: $\mathbf{TS}_{\mathrm{N}}$ (no stimulation), $\mathbf{TS}_{\mathrm{SC}}$ (synchronized tactile simulation), and $\mathbf{TS}_{\mathrm{SQ}}$ (sequential tactile stimulation), and let the participant know that s/he may or may not experience these tactile stimulations during the study. The experimenter asked the participant to adjust the position of the device along with the seat-belt and the tactile intensity for her/his best perception and comfort. Based on findings from prior works [3, 16, 25, 30], we set the personalized and fixed GBR as 80% of the mBR. To obtain the baseline EDA and mBR, the participant was asked to rest for 2-min. The on-road passenger study consisted of 4 driving segments. For the first 3 segments, the aSpire was operated in randomized order $\mathbf{TS}_{\mathrm{N}}$, $\mathbf{TS}_{\mathrm{SC}}$ (Fig. 4(a)), and $\mathbf{TS}_{\mathrm{SQ}}$ (Fig. 4(b)). Over the first 3 segments, the experimenter did not expose the purpose of the device. However, before the last segment, which provided the sequential stimulation (denoted as $\mathbf{TS}_{\mathrm{SQE}}$), the experimenter provided the following explanation of the aSpire: *"The purpose of this device is for helping you control your breath. The operation cycle of the stimulation is customized based on your BR. You can try to engage your breathing with the stimulation only if you feel. However, it is totally up to you to disengage with the device, then just breath normally as you want. You do not have to try hard to find the correct feeling and follow."* All of the survey questionnaires can be found in Appendix.

We were interested in investigating the effect of sequential tactile patterns which can render a greater variety of patterns than the synchronized pattern and deliver directional information (flow). Also, we thought that the round-trip flow of the sequential pattern could remind the users of the direction of in/exhalation through their lungs. Therefore, we ran the sequential tactile pattern for the last segment of the study ($\mathbf{TS}_{\mathrm{SQE}}$) to focus more on a certain pattern.

6.3 Results

A total of 15 participants ranging from 20 to 38 years old ($M = 28.4$, $SD = 4.72$) took part in the study (8 females and 7 males). 10 participants reported having prior experience in breathing exercises. We computed the perceived stress based on [12] via PSS survey, and had 3 participants reported low perceived stress, while the rest of participants reported moderate perceived stress. The physiological signals considered in this study are BR and EDA. Fig. 5 depicts the raw signals of the participant-14 (P14) collected during the experiment.

6.3.1 *H.1 & 3: Engagement in the aSpire.*

We used the BR and the tactile feedback perception to evaluate the engagement level of the passengers in the aSpire. The average GBR obtained during the 2-min of rest period was 10.8 (sd=3.05). We used each person's GBR to normalize the BR to evaluate the difference in the BR between the different segments. The normalized BR (NBR) close to 1 indicates a full engagement in the device feedback. Fig. 6 shows that the NBR of the $\mathbf{TS}_{\mathrm{SC}}$ and $\mathbf{TS}_{\mathrm{SQ}}$ are at the same level of the $\mathbf{TS}_{\mathrm{N}}$. The NBR of the $\mathbf{TS}_{\mathrm{SQE}}$ is the lowest, with a median value of 0.96, slightly less than 1. 53.3% of the participants were able to fully engage with the tactile feedback. The difference between the conditions was statistically significant (Friedman chi-squared = 25.64, df = 3, $p<0.001$). The pairwise Wilcoxon test was then applied with the Bonferroni correction. The difference was significant between each of the $\mathbf{TS}_{\mathrm{N}}$, $\mathbf{TS}_{\mathrm{SC}}$, and $\mathbf{TS}_{\mathrm{SQ}}$ when compared to the $\mathbf{TS}_{\mathrm{SQE}}$. During the $\mathbf{TS}_{\mathrm{SQE}}$, 80% of the participants were able to lower 24.8% of their average BR compared to when they experienced the $\mathbf{TS}_{\mathrm{N}}$.

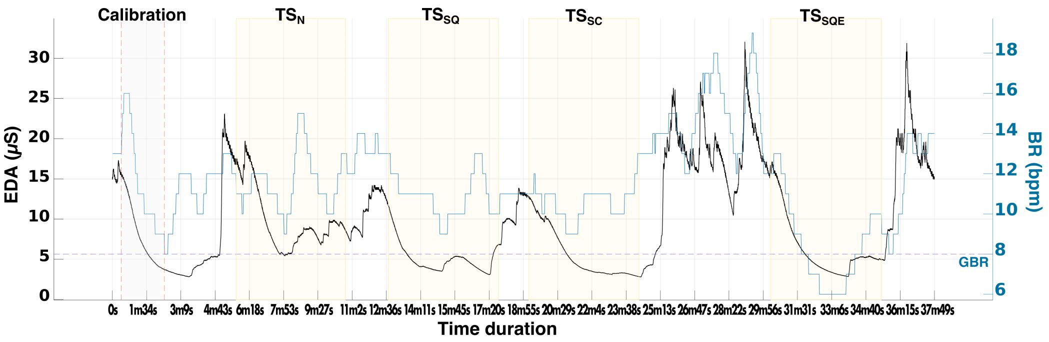

Figure 5: Illustration of raw EDA and BR signals: P14. (GBR = 8 bpm) as one of examlples

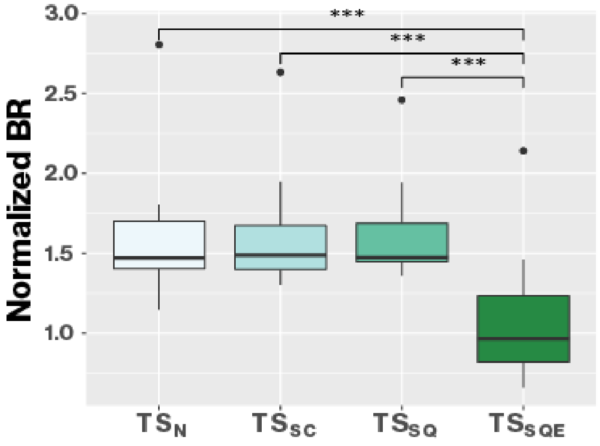

Figure 6: The boxplots of the normalized BR (by GBR) per condition. Note that $***$ indicates $p \leq 0.001$.

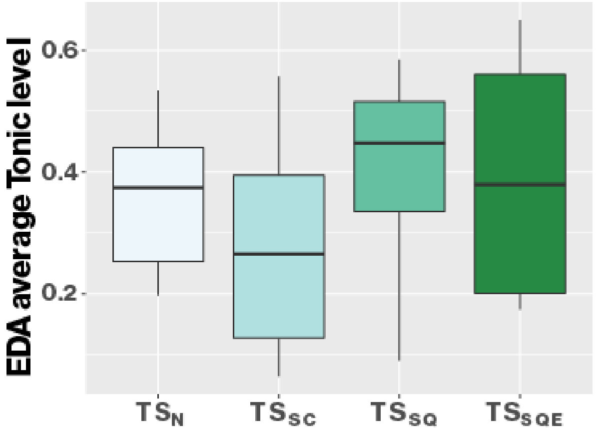

Figure 7: Boxplots of the mean normalized EDA tonic level, for the four segments conditions.

Compared to the $\mathbf{TS}_{\mathrm{N}}$, the NBR of the $\mathbf{TS}_{\mathrm{SC}}$ and $\mathbf{TS}_{\mathrm{SQ}}$ was not significantly lower, which means that **H.1.1** is not confirmed unless the brief disclosure of the device's information was given. However, the difference of the $\mathbf{TS}_{\mathrm{SQE}}$ was significant compared to the $\mathbf{TS}_{\mathrm{N}}$, which confirms **H.1.2**.

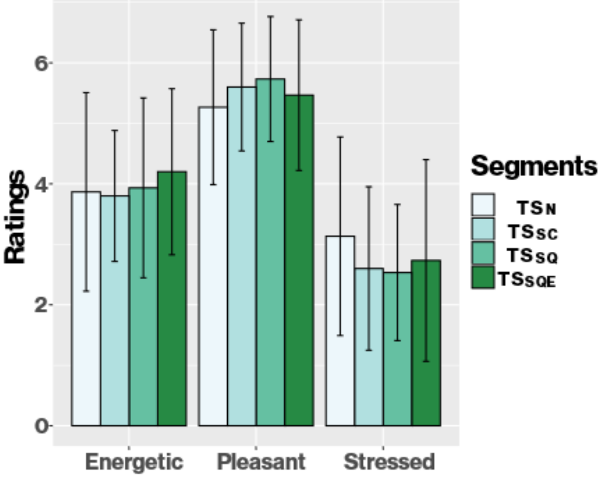

Figure 8: Mean (bar) and standard deviation (line) of the subjective energy, pleasantness, and stress ratings for each conditions.

For the $\mathbf{TS}_{\mathrm{SC}}$, 60% of the participants reported that they were inhaling when the pouches were inflating and exhaling when the pouches were deflating. 2 participants engaged in the opposite way and 4 were confused when to inhale or exhale. For the $\mathbf{TS}_{\mathrm{SQ}}$, 40% of the participants reported that they inhaled when the actuator inflated from the bottom to top and exhaled when it inflates from top to bottom. 26.7% of them reported the opposite way, and 1 participant felt that the middle pouch inflation triggered him/her to inhale. These findings confirm that even without receiving a prior explanation and training on how to match the breathing cycles with the aSpire's pattern movement, most participants selected the same way of engaging in the breathing guide of $\mathbf{TS}_{\mathrm{SC}}$ (**H.3**) but more varied engagement way for $\mathbf{TS}_{\mathrm{SQ}}$. This needs to be more investigated in future user studies, where we monitor the participants' breathing phase.

6.3.2 ***H.2: User acceptance of the aSpire.*** We considered the self-reports as well as the EDA to verify the effect of the aSpire on the arousal level associated with the users' acceptance of it. The participants answered how pleasant (valence), energetic (arousal), and stressed they were feeling during each segment. The ratings were provided on a Likert scale (1 - 7). Fig. 8 depicts the average of subjective ratings for the perceived energy, pleasantness and stress level, for the four different segments. The participants rated their energy level as medium with an average of 3.8 (sd=1.34). Fig. 8 shows that the reported arousal is highest for the $\mathbf{TS}_{\mathrm{SQE}}$ segment however there was no significant statistical difference between the segments. While pleasantness level was higher for all the stimulation segments with an average of 5.35 (sd=1.16) compared to the $\mathbf{TS}_{\mathrm{N}}$, the statistical difference was not significant. This reflects that the experience induced a positive valence and the stimulation did not reduce the pleasure level. The perceived stress level was reported to be low for all the experience, with an average of 2.4 (sd=1.26). However, there is no significant difference of the perceived stress between the segments, which means that the tactile stimulation did not evoke any extra stress.

We decomposed the EDA into tonic and phasic levels [7]. The total number of peaks and the normalized average tonic EDA were extracted to analyze the affect arousal. The statistical comparison of the EDA average tonic level showed that the difference was on the edge of statistical significance (Friedman chi-squared = 7.4, df = 3, p-value = 0.06). Fig. 7 shows that the EDA level of the $\mathbf{TS}_{\mathrm{SC}}$ is the lowest. This suggests that the $\mathbf{TS}_{\mathrm{SC}}$ is the least arousing. When comparing the total number of peaks for the 4 segments, there is no significant difference (Friedman chi-squared = 5.36, df = 3, p-value = 0.15). These findings validate the **H.2**.

6.3.3 ***User perception of the tactile stimulation.*** 46.66% of the participants reported that they perceived the stimulation during the $\mathbf{TS}_{\mathrm{SC}}$, while 87% of them perceived a feedback during the $\mathbf{TS}_{\mathrm{SQ}}$ and 93% during the $\mathbf{TS}_{\mathrm{SQE}}$. Fig. 9 shows the counts of the selections for the different feelings reported. The $\mathbf{TS}_{\mathrm{SQ}}$ led more participants to feel it as someone's presence than the $\mathbf{TS}_{\mathrm{SC}}$. No one reported the $\mathbf{TS}_{\mathrm{SC}}$ as poking. It is clear that the both provided a feeling of massaging in the context of commuting. However, the $\mathbf{TS}_{\mathrm{SQ}}$ was felt as massaging more than the $\mathbf{TS}_{\mathrm{SC}}$.

6.3.4 ***User Preferences.*** Fig. 10(a) shows the participants' preferred stimulation pattern. One participant said that the preference would depend on his/her mood. Fig. 10(b) shows the survey result on the aSpire's potential usage. The participants were also asked where they want to have the device attached. 6 participants reported that they would use it in airplane seat belts, 3 in backpack straps, 2 in office chairs, 2 in a hospital bed, and 1 for a pillow and another for a wristband. ***Open Remarks*** *(including feedback from 3 test-drives):* 4 participants reported that the stimulation felt like hugging their pet or kids, and other 4 reported that the device helped them to focus more on their breathing and stay calm. P5 highlighted the usefulness of the aSpire attached to the seat-belt to appreciate the wear of the seat belt while it is usually uncomfortable to put. Also, when he experienced stressful events happened outside like hearing a car horn, sudden stop, he mentioned that aSpire helped him bring back his attention to its calming feeling and ignore the stressful events. P7 mentioned, *"I think this device gives me a good excuse to focus on something very calming and my own time when share a ride with someone who is not close to me but feel like being forced to socially engage with him/her".* 2 participants commented that the $\mathbf{TS}_{\mathrm{SQ}}$ would be beneficial for awakening driver. P17 said, *"I will definitely use this especially when I commute to work, which is stressful, since it gives me very relaxing yet still awakening feeling which makes my mind clear like practicing meditation".*

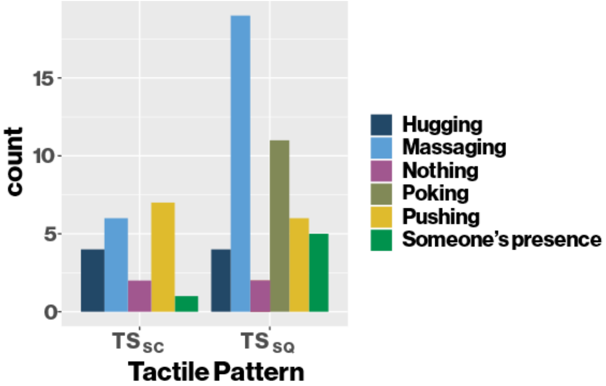

Figure 9: Perceived feelings by Synchronized and sequential pattern

7 DISCUSSION AND FUTURE WORK

7.1 Toward Effortless BR Control and Perceptions on Different Tactile Patterns

Only 20% of the participants guessed the device's purpose correctly during the first 3 driving segments. Whether the participants knew the purpose of the aSpire or not, engaging with the $\mathbf{TS}_{\mathrm{SQ}}$. caused no significant difference in their pleasant, energetic, stress level, and EDA. Once we disclosed the brief information and gave them freedom to engage with the device during the final segment, participants quickly lowered their BR close to their GBR, which indicates that the aSpire facilitated users' BR regulation, even though it did not "force" a particular BR before they knew about the purpose

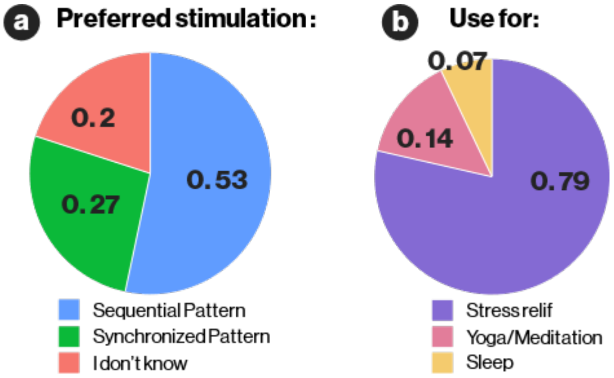

Figure 10: (a) Preferred stimulation (b) Potential usage of aSpire

of the device. We plan to investigate the effect of disclosing the purpose of the device to the participants on the engagement and acceptance of aSpire for the $\mathbf{TS}_{\mathrm{SC}}$.

Most of the participants inhaled when the $\mathbf{TS}_{\mathrm{SC}}$ was in inflation. We suggest 3 potential interpretations: 1) Participants were likely (unconsciously) to inhale to resist the inflation of aSpire to secure their space in between their body and the seat-belt; 2) participants naturally mimicked the motion of aSpire since it felt like motions of the respiratory system or 3) someone's presence so that they naturally synchronized with its behavior [22, 28]. We suggest further testing of these explanations as future work. Most participants felt the $\mathbf{TS}_{\mathrm{SC}}$ more subtle than $\mathbf{TS}_{\mathrm{SQ}}$ even with the same stimulation intensity. This might be because $\mathbf{TS}_{\mathrm{SQ}}$ keeps varying the stimulation location over the chest area while the $\mathbf{TS}_{\mathrm{SC}}$ produces more globally distributed stimulation by all 3 actuators. Although a few participants did not tell the difference between the $\mathbf{TS}_{\mathrm{SC}}$ and $\mathbf{TS}_{\mathrm{N}}$ during the ride on a bumpy road, their body might unconsciously notice it, since the EDA values was the lowest during the $\mathbf{TS}_{\mathrm{SC}}$. However, since the difference between the EDA levels showed borderline significance, delving into rendering tactile stimulation that produces significant impact on participants' arousal level remains as future work.

7.2 Effect of aSpire on the Car Occupants Stress Level and Beyond

The induced riding comfort reported by the passengers makes it a potential in-cabin feature applicable to future public transportation, flight, limos, and autonomous vehicles which will face a challenge of "promoting a sense of comfort in passengers" [15]. However, to claim that the aSpire can be used for relieving the users' stress during any stressful events and its effect on the users' foreground task performance, a protocol that directly induces stressful tasks should be designed. With the aSpire's verified safety (e.g. causing no extra stress or discomfort) in the on-road environment, we plan to test it with drivers in real-world driving. This may help them to subconsciously engage with the breathing intervention, without altering the main task and reducing road safety, which has been a concern in evaluating vibrotactile feedback [3, 30]. Moreover, reflecting on the reported potential usage of aSpire, we plan to evaluate the efficacy and mobility of aSpire during a variety of daily activities.

8 CONCLUSION

To expand the ability in HCI to conduct studies and design interfaces that help people regulate their breathing, we introduced–aSpire–a clippable pneumatic-tactile feedback device that nudges users to effortlessly regulate their BR. We conducted a user study in a real-world commuting setting to evaluate the effectiveness of aSpire in guiding the BR and assess the participants' perception of different tactile stimulation patterns. The results showed that the participants were able to engage with aSpire while maintaining a high level of pleasantness and energy, and evoking no extra stress. 80% of the participants reduced their average BR by 24.8% of their baseline. 93% of them selected the aSpire to be deployed for stress relief and meditation, which led us to highlight its potential applications in daily routines.

ACKNOWLEDGMENTS

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A APPENDIX

User Study Survey Questionnaires: https://github.com/mallcong/aSpire

REFERENCES

[1] ATPA. 2020. *2020 Public Transportation Fact Book* (71 ed.). Technical Report. https://www.apta.com/wp-content/uploads/APTA-2020-Fact-Book.pdf
[2] Ruben T. Azevedo, Nell Bennett, Andreas Bilicki, Jack Hooper, Fotini Markopoulou, and Manos Tsakiris. 2017. The calming effect of a new wearable device during the anticipation of public speech. *Scientific Reports* 7, 1 (may 2017). https://doi.org/10.1038/s41598-017-02274-2
[3] Stephanie Balters, Matthew L. Mauriello, So Yeon Park, James A. Landay, and Pablo E. Paredes. 2020. Calm Commute: Guided Slow Breathing for Daily Stress Management in Drivers. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 1 (mar 2020), 1–19. https://doi.org/10.1145/3380998
[4] Stephanie Balters, Elizabeth L. Murnane, James A. Landay, and Pablo E. Paredes. 2018. Breath Booster!: Exploring In-Car, Fast-Paced Breathing Interventions to Enhance Driver Arousal State. In *Proceedings of the 12th EAI International Conference on Pervasive Computing Technologies for Healthcare - PervasiveHealth '18*. ACM Press. https://doi.org/10.1145/3240925.3240939
[5] Yuki Ban, Hiroyuki Karasawa, Rui Fukui, and Shin' ichi Warisawa. 2018. Relaxushion: controlling the rhythm of breathing for relaxation by overwriting somatic sensation. In *SIGGRAPH Asia 2018 Emerging Technologies on - SA '18*. ACM Press. https://doi.org/10.1145/3275476.3275492
[6] beurer. [n.d.]. Stress releaZer. https://www.beurer.com/web/gb/products/wellbeing/shiatsu-and-massage/stress-releazer/stress-releazer.php
[7] Wolfram Boucsein. 2012. *Electrodermal activity*. Springer Science & Business Media.
[8] Richard P. Brown and Patricia L. Gerbarg. 2005. Sudarshan Kriya Yogic Breathing in the Treatment of Stress, Anxiety, and Depression: Part I—Neurophysiologic Model. *The Journal of Alternative and Complementary Medicine* 11, 1 (feb 2005), 189–201. https://doi.org/10.1089/acm.2005.11.189
[9] U.S Census Bureau. 2018. *2018 American Community Survey 1-Year Estimates*. Technical Report. https://data.census.gov/cedsci/table?q=commute%20time&hidePreview=false&tid=ACSST1Y2018.S0801
[10] Sibela Chinareva, Jack Jones, Nuha Tumia, Dan Kumpik, Palvi Shah, and Aluna Everitt. 2020. Lotus: Mediating Mindful Breathing. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM. https://doi.org/10.1145/3334480.3382938
[11] Kyung Yun Choi and Hiroshi Ishii. 2020. ambienBeat: Wrist-worn Mobile Tactile Biofeedback for Heart Rate Rhythmic Regulation. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM. https://doi.org/10.1145/3374920.3374938
[12] Sheldon Cohen, Tom Kamarck, and Robin Mermelstein. 1983. A Global Measure of Perceived Stress. *Journal of Health and Social Behavior* 24, 4 (dec 1983), 385. https://doi.org/10.2307/2136404
[13] Jean Costa, Alexander T. Adams, Malte F. Jung, François Guimbretière, and Tanzeem Choudhury. 2016. EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM. https://doi.org/10.1145/2971648.2971752
[14] M C Gameiro da Silva. 2002. Measurements of comfort in vehicles. *Measurement Science and Technology* 13, 6 (apr 2002), R41–R60. https://doi.org/10.1088/0957-0233/13/6/201
[15] Nicole Dillen, Marko Ilievski, Edith Law, Lennart E. Nacke, Krzysztof Czarnecki, and Oliver Schneider. 2020. Keep Calm and Ride Along: Passenger Comfort and Anxiety as Physiological Responses to Autonomous Driving Styles. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM. https://doi.org/10.1145/3313831.3376247
[16] Asma Ghandeharioun and Rosalind Picard. 2017. BrightBeat: Effortlessly influencing breathing for cultivating calmness and focus. *Conference on Human Factors in Computing Systems - Proceedings* Part F1276 (2017), 1624–1631. https://doi.org/10.1145/3027063.3053164
[17] Apple Inc. [n.d.]. Apple Watch Breathe App. https://support.apple.com/ko-kr/guide/watch/apd371dfe3d7/watchos
[18] Gerwyn Hughes Tim Watson James A. Johnstone, Paul A. Ford and Andrew T. Garrett. 2012. Bioharness Multivariable Monitoring Device: Part. I: Validity. *Journal of Sports Science and Medicine* 11(3) (2012), 400–408.

[19] Gerwyn Hughes Tim Watson James A. Johnstone, Paul A. Ford and Andrew T. Garrett. 2012. Bioharness Multivariable Monitoring Device: Part. II: Reliability. *Journal of Sports Science and Medicine* 11(3) (2012), 409–417.

[20] Ravinder Jerath, Molly W. Crawford, Vernon A. Barnes, and Kyler Harden. 2015. Self-Regulation of Breathing as a Primary Treatment for Anxiety. *Applied Psychophysiology and Biofeedback* 40, 2 (apr 2015), 107–115. https://doi.org/10.1007/s10484-015-9279-8

[21] NEIL E KLEPEIS, WILLIAM C NELSON, WAYNE R OTT, JOHN P ROBINSON, ANDY M TSANG, PAUL SWITZER, JOSEPH V BEHAR, STEPHEN C HERN, and WILLIAM H ENGELMANN. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology* 11, 3 (jul 2001), 231–252. https://doi.org/10.1038/sj.jea.7500165

[22] Leonie Koban, Anand Ramamoorthy, and Ivana Konvalinka. 2017. Why do we fall into sync with others? Interpersonal synchronization and the brain's optimization principle. *Social Neuroscience* (nov 2017), 1–9. https://doi.org/10.1080/17470919.2017.1400463

[23] Mikki Kressbach. 2018. Breath work: mediating health through breathing apps and wearable technologies. *New Review of Film and Television Studies* 16, 2 (mar 2018), 184–206. https://doi.org/10.1080/17400309.2018.1444459

[24] Inc. LDA Consulting, CIC Research. 2019. 2019 STATE OF THE COMMUTE SURVEY. *National Capital Region Transportation Planning Board COMMUTER CONNECTIONS PROGRAM* (2019). https://www.mwcog.org/file.aspx?&A=1AAuS26tuk0qvTVF52Q7%2bD87l582VWw4yNkHhrI8JrM%3d

[25] Grace Leslie, Asma Ghandeharioun, Diane Zhou, and Rosalind W. Picard. 2019. Engineering Music to Slow Breathing and Invite Relaxed Physiology. In *2019 8th International Conference on Affective Computing and Intelligent Interaction (ACII)*. IEEE. https://doi.org/10.1109/acii.2019.8925531

[26] A. Macaranas, A. N. Antle, and B. E. Riecke. 2015. What is Intuitive Interaction? Balancing Users' Performance and Satisfaction with Natural User Interfaces. *Interacting with Computers* 27, 3 (feb 2015), 357–370. https://doi.org/10.1093/iwc/iwv003

[27] Pardis Miri, Emily Jusuf, Andero Uusberg, Horia Margarit, Robert Flory, Katherine Isbister, Keith Marzullo, and James J. Gross. 2020. Evaluating a Personalizable, Inconspicuous Vibrotactile(PIV) Breathing Pacer for In-the-Moment Affect Regulation. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM. https://doi.org/10.1145/3313831.3376757

[28] Reneeta Mogan, Ronald Fischer, and Joseph A. Bulbulia. 2017. To be in synchrony or not? A meta-analysis of synchrony's effects on behavior, perception, cognition and affect. *Journal of Experimental Social Psychology* 72 (sep 2017), 13–20. https://doi.org/10.1016/j.jesp.2017.03.009

[29] Athina Papadopoulou, Jaclyn Berry, Terry Knight, and Rosalind Picard. 2019. Affective Sleeve: Wearable Materials with Haptic Action for Promoting Calmness. In *Distributed, Ambient and Pervasive Interactions*. Springer International Publishing, 304–319. https://doi.org/10.1007/978-3-030-21935-2_23

[30] Pablo E. Paredes, Yijun Zhou, Nur Al-Huda Hamdan, Stephanie Balters, Elizabeth Murnane, Wendy Ju, and James A. Landay. 2018. Just Breathe: In-Car Interventions for Guided Slow Breathing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (mar 2018), 1–23. https://doi.org/10.1145/3191760

[31] Mirjana Prpa, Ekaterina R. Stepanova, Thecla Schiphorst, Bernhard E. Riecke, and Philippe Pasquier. 2020. Inhaling and Exhaling: How Technologies Can Perceptually Extend Our Breath Awareness. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3313831.3376183

[32] Sanguinetti, Angela; Kurani, Ken; Ferguson, Beth. 2018. Is It OK to Get in a Car with a Stranger: Risks and Benefits of Ride-pooling in Shared Automated Vehicles. (2018). https://doi.org/10.7922/G27M064Z

[33] Auditya Purwandini Sutarto, Muhammad Nubli Abdul Wahab, and Nora Mat Zin. 2012. Resonant Breathing Biofeedback Training for Stress Reduction Among Manufacturing Operators. *International Journal of Occupational Safety and Ergonomics* 18, 4 (jan 2012), 549–561. https://doi.org/10.1080/10803548.2012.11076959

[34] TheaWellbeing. [n.d.]. Melo: Helping you stay calm in a busy world. Kickstarter. https://www.kickstarter.com/projects/theawellbeing/melo-helping-you-stay-calm-in-a-busy-world

[35] Frederik Mørch Valsted, Christopher V. H. Nielsen, Jacob Qvist Jensen, Tobias Sonne, and Mads Møller Jensen. 2017. Strive: exploring assistive haptic feedback on the run. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction - OZCHI '17*. ACM Press. https://doi.org/10.1145/3152771.3152801

[36] Christopher D. Wickens. 2008. Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50, 3 (jun 2008), 449–455. https://doi.org/10.1518/001872008x288394

[37] Bin Zhu, Anders Hedman, Shuo Feng, Haibo Li, and Walter Osika. 2017. Designing, Prototyping and Evaluating Digital Mindfulness Applications: A Case Study of Mindful Breathing for Stress Reduction. *Journal of Medical Internet Research* 19, 6 (jun 2017), e197. https://doi.org/10.2196/jmir.6955

[38] Jing Zhu and Yingling Fan. 2017. Daily Travel Behavior and Emotional Well-Being: A comprehensive assessment of travel-related emotions and the associated trip and personal factors. (2017).