Calm Commute: Guided Slow Breathing for Daily Stress Management in Drivers

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Commutes provide an opportune time and space for interventions that mitigate stress–particularly stress accumulated during the workday. In this study, we test the efficacy and safety of haptic guided slow breathing interventions of short duration while driving. We also present design and experimental implications for evolving these interventions from prior simulator to moving vehicle scenarios. We ran a controlled study (N=24) testing a haptic guided breathing system in a closed circuit under normal and stressful driving conditions. Results show the intervention to be successful in both user adoption and system effectiveness with an 82% rate of engagement in intervention and clear reduction of breathing rate and physiological arousal, with no effect on driving safety and minimal effect on performance. The haptic intervention received positive acceptance from the participants: all indicated a willingness to engage with the intervention in the future and all rated the intervention as safe for traffic applications. The results of this study encourage further investigations exploring the use of the intervention on public roads and monitoring for longitudinal health benefits.

CCS Concepts: • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*; • **Applied computing** → *Psychology*; • **Computer systems organization** → **Sensors and actuators**.

Additional Key Words and Phrases: Deep Breathing, Slow Breathing, Guided Slow Breathing, Stress Management, Commute, Intervention

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1 INTRODUCTION

Everyday, 87% of the labor force in the US (or 127 million people) spend an average of 1 hour commuting by car [17]. Data from the American Psychological Association (APA) survey on stress (2013) has shown that people find it difficult to manage their work-related stress mainly due to lack of time and lack of will power [1]. The commute is therefore an opportune time for an intervention to reduce the stress accumulated throughout the day.

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Fig. 1. Participant engaging with the breathing intervention while driving in the closed circuit.

As a result, there have been a number of recent proposals aiming to re-purpose the commute and transform it into time for managing stress by leveraging biofeedback [9], movement [21], and guided breathing [3, 23].

In our work, we present the first on-road, controlled study of a haptic seat that supports short-duration guided breathing exercises in the car. Contributions of this work include: (i) validation of prior simulator findings for in-car breathing interventions in an on-road scenario, (ii) evidence of the efficacy of these techniques in both normal and stressful driving conditions, and (iii) validation of safety and performance driving parameters using commercially available sensors, some already deployed in modern cars.

To conduct our research we formulated the following research questions:

- R1: Can an in-car guided breathing system lower a driver's breathing rate and arousal level? If so, how long do such effects sustain over time? And, is there a difference in terms of efficacy and user preference between in-car guided breathing interventions administered during normal and stressful driving conditions?
- R2: Are in-car guided breathing interventions safe and, if so, would it be safe to test them in traffic?

Results show an intervention adoption rate of 82%, and further validate a reduction in breathing rate and physiological arousal for those who engaged with the intervention. Quantitative results show further that engaging with the intervention had no significant effects on driving safety; however, qualitative user feedback brings up a concern of applying the intervention on-the-road if a driver is already fatigued. Further qualitative analysis reveals an overall positive acceptance–all participants envisioned engaging with the intervention in the future. Additionally, all participants rated the intervention as safe for traffic applications.

2 BACKGROUND AND RELATED WORK

In this section, we provide background information on stress and the commute, discuss prior work on haptic in-car breathing interventions, and define the driving safety and performance metrics used in our study.

2.1 Background on Stress

The stress response is an evolutionary mechanism that mobilizes physical resources to help humans cope with challenges and life-threatening situations. The American Psychological Association differentiates between acute, episodic acute stress, and chronic stress [2]. In that sense, we understand stress as a psycho-physiological response to a stressor. While acute stress is a short-term response to a stressor from which individuals almost fully recover, experiencing frequent and constantly elevated levels of stress (episodic acute and chronic stress) is associated with a variety of patho-physiological risks including cardiovascular diseases and immune deficiencies, impaired quality of life, and shortened life expectancy [7, 13, 16]. As noted in the introduction, the aim of our work is to reduce stress accumulated during the workday and mitigate driving-induced stress that could otherwise exacerbate stress-related symptoms [15]. In this work, we focus on the beneficial health effects of slow breathing which are well known and documented. For example, intentional slow breathing has been shown to activate

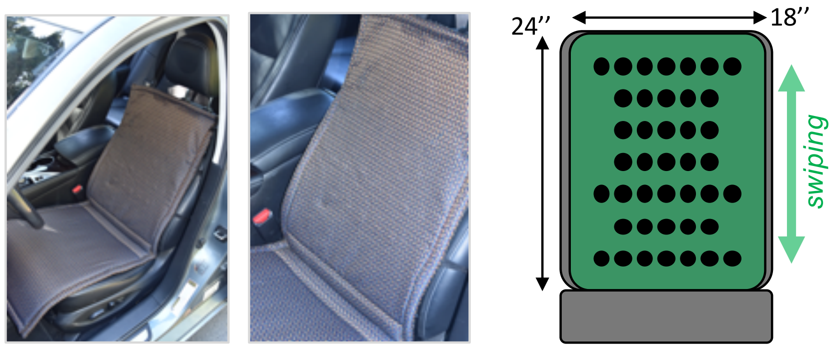

Fig. 2. Seat configuration covering a back space of 12x18 inch grid, able to produce a variety of haptic stimulation patterns.

the parasympathetic nervous system and thereby reduce physiological arousal as shown by decreases in heart rate [19, 33] and increases in heart rate variability [6, 32]. We investigate whether the concept of guided slow breathing interventions are feasible–that is effective and safe–in the driving context.

2.2 Haptic In-car Breathing Interventions

Recently there have been numerous proposals to rethink the commute and turn it into a time for stress management [3, 22, 23]. For example, Paredes, et al. [23] explored both slow breathing and fast breathing exercises as well as the efficacy of haptic and voice guidance commands in controlled within-subjects studies. Additionally, this work looked at the effects of driving environment (city vs. highway) and driving mode (manual vs. autonomous). Results validate the efficacy of guidance interventions in decreasing breathing rate and physiological arousal levels (i.e., heart rate variability) for both voice and haptic guidance – the latter being able to sustain its effects up to 2 minutes after removing the guided stimulus. Overall, participants preferred the haptic experience as it was perceived as more subtle. With this study, we extend the prior work by demonstrating the validity of this technique in naturalistic conditions, using a real car on a closed driving circuit. Compared to the prior work, we further expand the research scope to test the efficacy of the intervention to reduce the effects of acute stress by applying a stressor proven to work during a driving task (i.e., a math task followed immediately by the playing of heavy metal music) [22].

2.3 Driving Safety and Performance

An essential consideration with respect to the implementation of the intervention in traffic applications is meeting safety requirements. Although drivers today engage in numerous secondary tasks that are considered "safe" (e.g., hands-free conversing on the phone, eating/drinking, interacting with navigation systems or the radio), the intervention has a potential risk of pulling attention and focus away from the critical task of operating the vehicle which can degrade driving performance [23]. It is our aim to test beyond efficacy and examine whether safety levels can be maintained when introducing a breathing intervention that could have mild effects on cognitive and physiological performance.

Most safety and driving performance measures are outlined by SAE Standard J2944-201506 [28] which defines these terms in relation to actual incidents (e.g., time to collision) and other road users (e.g., distance gap to car in front). We chose to run our experiments in a short, closed circuit without additional traffic and use safety and performance measures that are applicable for a low speed driving scenario, including hard breaks and lane tracking compliance. In this work, we differentiate between driving safety and driving performance measures.

Safety is evaluated by counting the number of hard brakes (i.e., a fast brake in response to a sudden driving incident) [8] and severe lane-keeping violations (i.e., defined as an incident when the middle of the car touches and/or crosses either side lane [28]). *Performance* is measured by calculating: average speed, acceleration, braking, steering reversal rate, standard deviation from the center line, and mild to severe lane-keeping violations. While we classify severe lane-keeping violations as a safety risk (i.e., people could potentially risk crashing into the structural pillars of the garage), we do not consider mild lane-keeping violations as a safety concern on an empty road, as in the case of our study. However, mild lane deviations, which are incidents of one tire touching and/or crossing a lane on either side, would be classified with a different level of risk in other scenarios (e.g., high density traffic).

3 METHODOLOGY

We ran a between-subject study (see Figure 1) with twenty-four experienced commuters to test the efficacy and safety of haptic guided breathing interventions while driving on a closed circuit. The circuit was designed to simulate commute conditions, such as the inclusion of turns, straight pathways, and stop signs. Whilst the vehicle and physical environment were kept constant, participants were assigned to one of two groups, a guided breathing group (intervention) and a control group (no stimulus). While both groups were introduced to the haptic seat capable of administering a guided, slow breathing intervention prior to the participants' driving task, only the intervention group received guidance from the haptic seat during their drive. The experimental task consisted of a total of 8 minutes of driving in two conditions: normal and stressful driving (or "post-stressor driving") conditions. All participants were randomly assigned to one of two groups, and both groups were exposed to the normal and stress conditions (in random order to account for ordering effects) for within-subjects analyses (Table 2). The method described was approved by the Institutional Review Board of Stanford University.

Table 1. Between subject study design.

		Order of conditions	
Intervention group	(N=6)	Condition 1	Condition 2
	(N=6)	Condition 2	Condition 1
Control group	(N=6)	Condition 1	Condition 2
	(N=6)	Condition 2	Condition 1

3.1 Hypotheses and Variables

Based on the underlying physiological mechanism of the autonomic nervous system, we expect a decrease in physiological arousal caused by a decrease in breathing rate when people engage with the intervention. Specifically, we set out to test the following hypotheses:

- H1.1: Breathing Rate (BR) is lower during the intervention than before.
- H1.2: BR is lower after the intervention than before the intervention.
- H1.3: BR reduction during the intervention is higher than control.
- H1.4: BR reduction after the intervention is higher than the control.
- H2.1: Arousal is lower during the intervention than before.
- H2.2: Arousal is lower after the intervention than before.
- H2.3: Arousal reduction during the intervention is higher than control.
- H2.4: Arousal reduction after the intervention is higher than control.
- H3: Safety driving metrics (e.g., hard brakes) are not different during the intervention versus control.

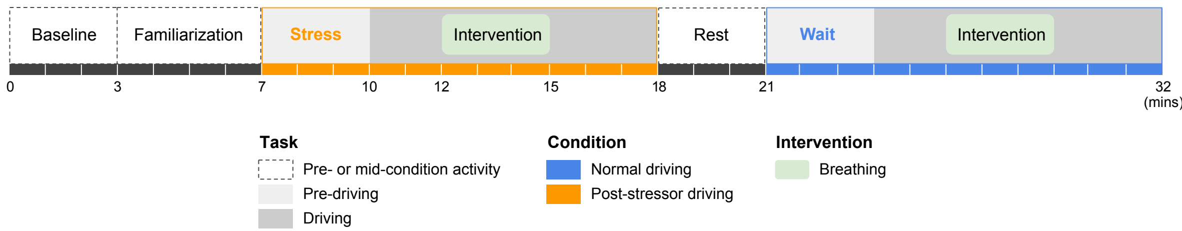

Fig. 3. Experimental procedure. The control group experienced same procedure except for the breathing interventions. Experimental conditions were counterbalanced for each group. The stressor (three minutes) was a *math task* adapted from Trier Social Stress Test.

- H4: Driving performance metrics are negatively affected during the intervention condition versus control.

To validate our hypotheses, we measured the following dependent variables:

- *Physiological:* (1) breathing rate (BR), (2) heart rate (HR), and (3) time-domain heart rate variability (HRV) using Root Mean Squared Standard Deviation (RMSSD)
- *Subjective self-reported stress:* (4) stress, (5) muscle tension, (6) arousal, and (7) valence
- *Driving safety:* (8) hard braking and (9) severe lane departures
- *Driving performance:* (10) mild lane departures, (11) average speed, (12) average acceleration, (13) average time on brakes, (14) steering reversal rate, and (15) deviation from the middle of the driving lane.

3.2 Apparatus

We used an Infinity Q50 instrumented to monitor participants' bio-metrics, behaviors, and driving dynamics (Figure 1). We designed our system for a single driver driving alone, as 76.4% of all US commuters drive alone [17], and because the presence of a passenger impacts a driver's behavior often reducing aggressive driving and increasing caution thus resulting in a safer driving experience [26, 34]. Here, we outline the instrumentation of the car and provide an overview of our haptic guidance system.

3.2.1 In-vehicle Testing System. Five GoPro cameras were installed to capture: (i) frontal and lateral views of the participant, as well as a view of the road ahead (see Figure 1) and (ii) lane markings on the left and right of the vehicle. All internal camera streams were merged via a QuadView Multiviewer system and recorded with Unix time stamps. The two exterior cameras were processed and aligned separately. We used a proprietary On-Board Device (OBD) dongle to collect the following Controller Area Network (CAN) bus data: speed (50Hz, mph), binary brake state (10 Hz, brake on/ brake off), and steering angle (100Hz, degrees, ranging between ± 450 degrees.)

To capture bio-metric data (e.g., breathing rate, heartbeat), we utilized the Zephyr BioHarness [18]. Piloting showed that the pressure sensor used to measure torso expansion was sensitive to pressure induced by participants' torso pressing against the arm and the seat of the car during turns. The frequency of turns was very similar to that of breathing (i.e., about 1 turn every 10 seconds), which made it difficult to remove these artifacts. As a workaround, we decided to displace the sensor from the side to a frontal position, move the seat to a more upright position, and instructed participants to drive with both hands on the steering wheel to facilitate a more rigid body posture.

3.2.2 Haptic Guidance System. To administer the interventions, we built a portable haptic vibrotactile seat cover composed of forty-one 2–3.6V linear resonant actuator (LRA) vibration motors arranged as shown in Figure 2. We programmed the motors to facilitate an up and down swiping pattern that has been successfully used to reduce breathing rate in prior studies [23]. For comfort, we cushioned the actuators with a thin foam layer (0.2

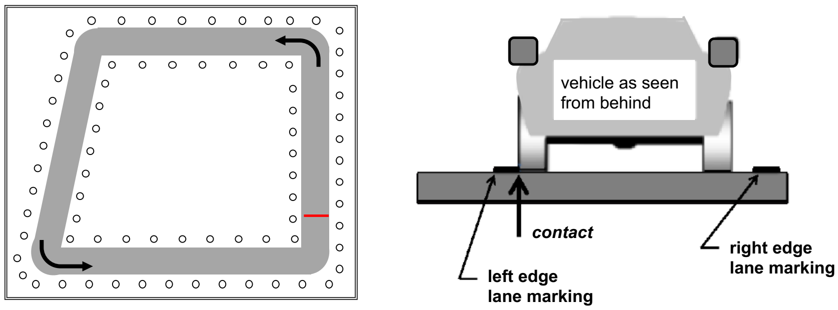

Fig. 4. (*Left*) Driving course. (*Right*) Lane departure as described by the SAE Standards for Operational Definitions of Driving Performance Measures [28].

inches) negligibly reducing the effect of the LRA motors. To ensure perception of the haptic stimulus, we asked participants to wear single layered, lightweight clothing.

3.3 Experimental Procedure

After consenting, participants filled out a pre-study questionnaire to collect data on demographics, driving experience, experience with breathing exercises, and experience with haptic stimulation. After attaching the physiological sensors the experimenter led participants to the car and instructed them to adjust the seat, mirrors, and temperature in the cabin to their comfort. During this time, the experimenter recorded the basal *average non-conscious* breathing rate (BR). Participants in both control and intervention conditions experimented with the haptic seat for 30 seconds and were trained to use the chair to reduce their basal BR (M = 12.24, Mdn = 12.35, SD = 2.32) to a 30% reduction of their baseline.

After this procedure, participants watched a three minute video of a beach scenario as a soothing baseline task, and drove five laps around the circuit (average duration M = 4 min 7 sec, SD = 1 min 4 sec) to familiarize themselves with the car and driving course. The experimenter instructed participants to imagine driving in a city and to obey all rules of the road including performing a full stop at any posted stop signs; the experimenter did not mention any speed limitation.

In counterbalanced order across participants, the experiment comprised two conditions with a pre-driving and driving task each (Figure 3). As a stressor, we chose a math task, which was adapted from the Tier Social Stress Test [11]. For three minutes, the participants had to count backwards from 2501 in steps of 13. If they gave a wrong answer or exceeded an answering period of four seconds, they had to start over. To keep risk at a minimum, we chose to expose participants to this task while sitting in the parked car (with the engine running). The subsequent *driving* task lasted a total of 8 minutes: 2 minutes of stressed/calm driving, 3 minutes with/without guided breathing intervention, and 3 minutes of post-intervention driving). While the intervention group received the haptic stimulus, the control group did not. As a pre-driving task for the "normal driving" condition, we included a 3-min long waiting period. The participants were instructed to wait in the parked car (with the engine running). We included this task as "neutral" stimulus (in comparison to, e.g., watching a soothing video) and to avoid different experimental lengths across the groups. The control and intervention driving tasks were separated by a three minutes long wash out or "rest" period. Between each task, we prompted participants with a questionnaire (see section "Self-reported Stress Metrics"). The procedure concluded with a post-study questionnaire, which included inquiries about which scenarios people may prefer to use this intervention (e.g. during a red light, on a

Table 2. Description of commute cohort.

Group	**Age (years)**	**Drivers license (years)**	**Commute time by day (# of participants)**				**Driving style 0 = cautious 100 = aggr.**	**Deep breathing (# of participants)**	
			<30min	**30min-1h**	**1-2h**	**>2h**		**Daily**	**Never**
Intervention	M = 40.3 SD = 12.4	M = 22.8 SD = 11	3	4	2	3	M = 55.7 SD = 17.5	5	1
Control	M = 40.0 SD = 13.3	M = 21.4 SD = 11.8	3	4	4	1	M = 54.4 SD = 17.1	7	4

highway). Participants were provided with insurance through the University upon validation of their driver's license and compensated with an Amazon gift card at the end of the study.

3.4 Experimental Conditions

Participants were randomly assigned to one of four conditions. First, they were divided into two between-subjects groups: (i) an *intervention* group with haptic guided breathing, and (ii) a *control* group. Each group was assigned to two within-subjects conditions presented in a randomized order (i.e., a then b, or b then a): (a) math stressor while parked + stressful driving, or (b) do nothing while parked + normal driving. To induce stress, we applied a previously used stressor for driving tasks [12, 22]. This stressor is composed of two parts: (i) three minutes of a *math task* adapted from Trier Social Stress Test (TSST) [11] (e.g., subtracting recursively from 1551, in steps of 13) with penalties for errors and delays, and (ii) a sequence of the heavy metal song *"At the Heart of Winter"* by Immortal[1] applied during the first two minutes of driving to maintain the stress caused by the math task.

3.5 Driving Course

We conducted the experiment in an underground parking garage without traffic set out to simulate a typical driving scenario that might make up parts of a simple commute. Within the garage we were able to set a 0.35 mile long driving course that included four left turns (Figure 4). To set the course, we taped white lane markings at a distance of 12 feet following standards for city/neighbourhood roads [29]. Presenting a slight hazard, structural pillars bordered the driving course at a distance of approximately six feet from each lane marking. During the entire experiment, participants drove in the same direction to simulate a familiar (and tedious) portion of a commute (i.e., the intervention is intended to be engaged at different points in the commute but not for the entire duration).

3.6 Participants

We invited a total of N = 24 (12 female, 12 male) commuters to participate in the study. Participants were all experienced drivers with an average age of (M = 40.2, SD = 12.9) years and with (M = 22.1, SD = 11.4) years of valid driver's license across groups (see Table 2 for detailed descriptions for each groups). All participants had normal or corrected-to-normal hearing and vision. All participants reported to commute at least a few times per week with a daily length ranging between less than 30 minutes to more than 2 hours. Self-reports of driving style indicated most participants were moderately aggressive drivers across both groups.

With respect to experience with breathing exercises and haptics, participants were mixed. About half of the participants reported practicing some form of slow breathing on a daily or weekly basis as part of yoga, martial arts, or swim practice. The remaining one fifth reported having no such experience. Eighty percent of the

[1]https://www.youtube.com/watch?v=VeOlPQqJR-o

participants reported prior experience with haptics, in the form of smartphone vibrations, wearables, and/or massage chairs. Three participants in the stressful driving condition and two of the normal driving condition had no prior experience with haptic interfaces (i.e., vibrations, pressure, etc.). When stressed in the car, participants reported listening to music, podcasts, or news. Some also reported singing, stretching, dancing, and talking to family or friends on the phone. Others reported that they engaged in "swearing at other drivers" or trying to "self massage" neck and leg muscles. All participants reported following instructions to not drink coffee or energizing drinks, eat heavy meals, take hot showers or baths, sleep, or do heavy exercise during the hour before the experiment.

3.7 Data Collection

We measured a total of four subjective, three physiological, six driving performance, and two driving safety metrics throughout the experiment.

3.7.1 Self-reported Stress Metrics. We obtained *self-report stress (SRS)* measurements via a simplified version of the Perceived Stress Scale (PSS): an 11-point scale with questions that included *"What is your current level of stress?"* and end points ranging from 0 - *"low"* to 10 - *"high"*. With the same 11-point scale, we further asked for the self-reported level of *physical tension* from 0 - *"low"* and 10 - *"high"*. Finally, participants completed the Affect grid scale that looks at *arousal* from 0 - *"sleepy"* to 10 - *"energized"* and *valence* from 0 - *"unpleasant"* to 10 - *"pleasant"* [25].

3.7.2 Physiological Metrics. We acquired *breathing rate (BR)* (1 Hz) and ECG (250 Hz) data – to calculate *heart rate* and *heart rate variability (RMSSD)* – using a Zephyr BioModule Device (version 3.0) [18] and the companion Bluetooth application allowed access to real-time data during the experiment.

3.7.3 Driving Safety Metrics. We measured the following safety violations suited to a closed circuit that is free of traffic: the number of *severe lane departures* and the number of *hard braking* responses to sudden driving incidents [8]. SAE Standards for Operational Definitions of Driving Performance Measures [28] define lane departures (option B) as a situation in which a tire touches or crosses the inside of the lane marking (see Figure 4). Departures are considered "severe" once the center of the car touches or crosses the lane marking. While milder lane departures might be less risky on empty roads, we consider greater lane departures to be a violation of driving safety.

3.7.4 Driving Performance Metrics. With respect to driving performance measures, we calculated the *number of mild lane departures*, average *speed* (mph), average *acceleration* (m/s^2), *time on brake* (%), *steering reversal rate* (counts/segment), and *deviation from center line* (m).

4 ANALYSIS AND RESULTS

In this section we present evidence of the effectiveness of the stress stimulus, validation of our hypotheses, and a brief qualitative exploration of participant's interest in in-car slow breathing guidance systems.

4.1 Quantitative Analysis and Results

First, we validated whether the STRESSOR condition (math task) task induced higher stress levels than the WAIT condition for each group and whether there were differences in stress between the groups for each condition. Next, we looked at whether engaging with the intervention indeed reduced BR and related effects on arousal levels. Finally, we examined if driving data showed incidents of safety violations or changes in driving performance. We ran one-way repeated measures ANOVAs (or Friedman's ANOVAs in cases where data was not normally distributed) to test for differences within the time series (i.e., BEFORE, DURING, and AFTER the intervention), each

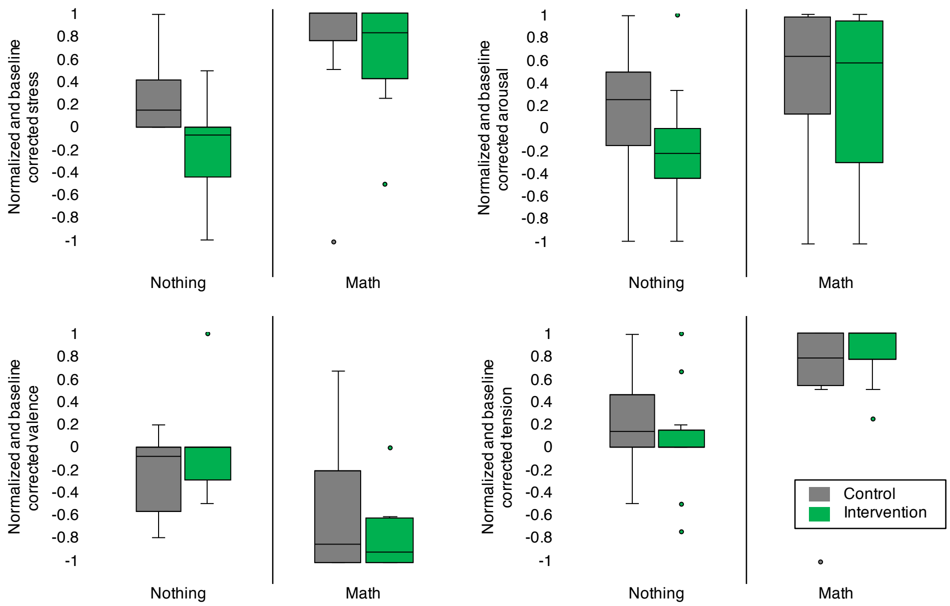

Fig. 5. Boxplots of normalized and baseline corrected levels of stress, arousal, valence, and tension.

condition (i.e., NORMAL DRIVING and POST-STRESSOR DRIVING), and both groups (i.e., intervention and control). Thereafter, we ran independent t-tests (or non-parametric Mann Whitney U tests) to test for differences in measures between the groups. Specifically we tested for differences in changes between BEFORE and DURING as well as BEFORE and AFTER intervention. We ran FDR procedure (Benjamin-Hochberg) to correct for multi-comparisons.

4.1.1 Stressor-stimulus Check. Prior to testing our hypotheses, we validated if our stress stimulus had the expected effect. Specifically, we validated that (i) the math task induced higher stress than the waiting condition and (ii) there was no difference in stress between the groups for both stimuli. We also normalized and corrected the measurements against the participant's baseline measurements (Figure 5). Our statistical results are summarized in Table 3. Mann-Whitney U tests revealed higher *stress* for MATH compared to WAITING for both groups. Thus, as expected, participants reported higher levels of stress in the presence of the stressor. *Tension* also showed equally higher values for MATH compared to WAITING for both groups. Further, perceived stress and tension were very strongly correlated ($r(46)= .966$, $p < .001$), which indicates a strong perceived relationship between stress and muscle tension. There were no differences in *arousal*. This difference between perceived stress and arousal indicates that people can be (physiologically) alert without perceiving this alertness as stress. Lastly, *valence* was lower during MATH compared to WAITING for both groups. These results indicate that participants perceived the math task as distressing rather than a neutral challenge. Overall, these findings suggest that we were successful in using the math task as a distressing stimulus.

When testing for differences between groups, Mann-Whitney U test revealed a significant difference in *perceived stress* for WAITING, but no differences for any other condition or measure. These findings suggest that participant randomization overall worked for the MATH condition; but that there might be a bias for the WAIT condition, which could result in variations in physiological or performance values.

Table 3. Statistical results. “p” = adjusted p-values after FDR correction for multiple comparisons within measures; and “p*” = further Bonferroni correction within main-effect ANOVA analyses.

Stressor-stimulus check

	Waiting vs. math		Intervention vs. control group	
Measure	**Intervention group**	**Control group**	**Waiting**	**Math**
Stress	U = 132, z = 3.482, p <.001	U = 124, z = 3.132, p <.01	U = 26, z = 2.729, p <.01	no
Tension	U = 134, z = 3.665, p <.001	U = 119, z = 2.275, p <.01	no	no
Arousal	no	no	no	no
Valence	U = 15, z = 3.409, p <.001	U = 32.5, z = 2.311, p <.05	no	no

Hypotheses testing: Within groups comparisons

	Normal driving		Post-stressor driving	
Measure	**Intervention group**	**Control group**	**Intervention group**	**Control group**
BR	F(2,14) = 5.553, p <.05 not after correction	no	F(2,16) = 11.801, p <.001 before vs. during p* <.001 before vs. after p* <.05	no
HR	no	no	no	no
RMSSD	no	F(2,22) = 6.648, p <.01 before vs. during p* <.05	F(2,16) = 6.454, p <.01 before vs. during p* <.01	no

Hypotheses testing: Between groups comparisons

	Normal driving		Post-stressor driving	
Measure	**Before vs. during**	**Before vs. after**	**Before vs. during**	**Before vs. after**
BR	no	no	no	no
HR	no	no	no	no
RMSSD	t(18) = 4.392, p <.001	no	t(19) = 4.805, p <.001	t(19) = 2.948, p <.01

4.1.2 Testing for Intervention Efficacy. We extracted the mean *breathing rate* measured in breaths per minute (brpm). We excluded one participant of the intervention group due to corrupted data. One participant, who only experienced the intervention during the post-stressor condition was excluded from the calm driving condition only. We then calculated the average BR for each task within the driving conditions. To account for the delay in Zephyr’s moving average window, we excluded the initial 45 seconds of each segment as described by the vendor, [18], and validated during pilots.

Based on this data, we verified whether every participant of the intervention group was engaged with the breathing intervention. To generate a benchmark, we calculated the natural variation in breathing rate throughout the baseline task across all participants. Results showed a value of 10%. Two participants of the intervention group did not reach this threshold. Thus, we observe an intervention adoption rate of roughly 82% in the participant population. For those participants who engaged with the intervention, we further validated that they reached efficacy of the breathing intervention by comparing to the target rate of 30%.

For NORMAL DRIVING, the difference between BR before (M = 14.20 brpm, SD = 3.42 brpm) and BR during (M = 12.06 brpm, SD = 2.26 brpm) was 15.04%, which is only half of the expected reduction in BR. For POST-STRESSOR

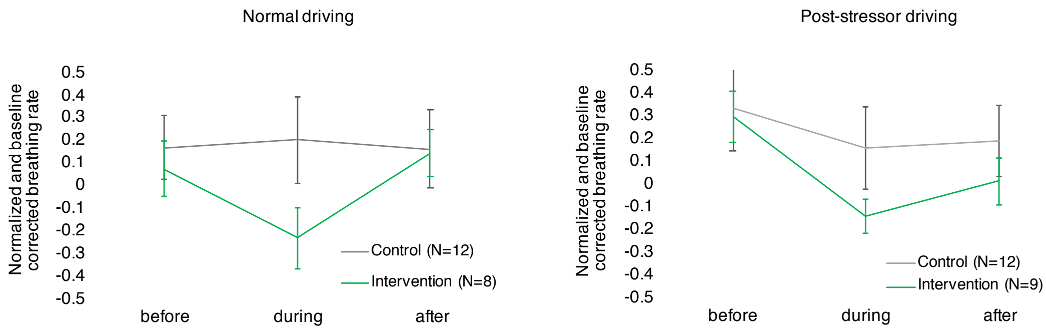

Fig. 6. Normalized and baseline corrected BR data for both conditions and both groups.

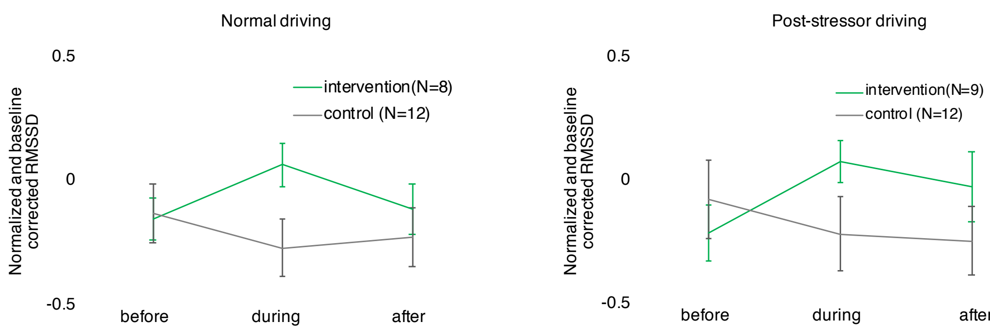

Fig. 7. Normalized and baseline corrected RMSSD data for both conditions and both groups.

DRIVING, the difference between BR before (*M* = 16.47 brpm, *SD* = 2.73 brpm) and BR during (*M* = 12.29 brpm, *SD* = 2.64 brpm) was 25.34% – closer to the targeted 30%. One potential reason for this difference in BR reduction might be that the majority of participants had higher initial breathing rates during POST-STRESSOR DRIVING compared to NORMAL DRIVING (though not significant p = .149) which facilitated a higher decrease in breathing rate. Further, we did not find any significant differences in initial breathing rates between the groups for either condition thus we can exclude group bias.

Having validated the efficacy of the intervention, we proceeded with statistical analyses of the normalized and baseline corrected BR data. For NORMAL DRIVING, repeated measures ANOVAs revealed statistically significant results for the intervention group, but not for the control group (see Table 3). However, after Bonferroni correction, we no longer detected significant differences. A potential reason for this missing significance could be the low power, which may be addressed by having more participants. Further, tests between the groups showed no significant differences either (though the decrease in BR upon intervention was almost significantly lower for the intervention group $t(18) = 1.978$, $p = .063$). For POST-STRESSOR DRIVING, data showed for the intervention group a significant decrease in BR between BEFORE and DURING as well as between BEFORE and AFTER. Tests between the groups showed no differences (though the decrease in BR upon intervention was almost significant for the intervention group $t(19) = 3.141$, $p = .045$).

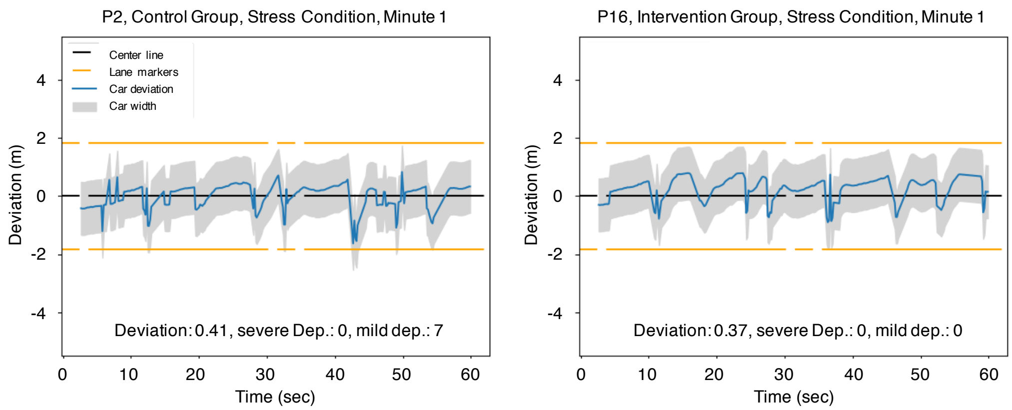

Fig. 8. Example visualizations of our lane analysis data showing the first minute of the stressful driving condition for participants in both the control (P2) and intervention (P16) conditions. Here we can observe numerous mild departures for P2 and a number of near-mild departures for P16, but no severe departures for either participant during this time frame.

We further processed raw ECG data using the Kubios HRV Software (v2.2) [31]. We set the artifact correction level to “none”. To detrend the time series, we applied smoothness priors regularization [31] with a regularization value of $\Lambda = 500$. We verified the results of the automatic peak detection via visual inspection, and manually corrected false negatives and false positives. We chose the root mean square of successive differences (RMSSD) as our heart rate variability (HRV) metric as it has been identified as a reliable stress indicator in prior work [30]. Finally, we extracted the corresponding mean heart rate (bpm) and RMMSD (ms) values from the software.

Heart rate. Statistical tests for heart rate data did not show any significant differences. These findings are consistent with prior work [23].

RMSSD. For NORMAL DRIVING, we observed no differences in the intervention group’s time series, but a decrease in RMSSD for the control group comparing the time segments corresponding to BEFORE and DURING. Between-group comparisons showed a higher increase in RMSSD for the intervention group comparing BEFORE and DURING, but this increase was only marginally for BEFORE and AFTER ($p = .051$). Hence, though we observe a tendency of increased RMSSD for the intervention group, the results do not demonstrate that the intervention was successful in decreasing physiological arousal in the form of increases in RMSSD. For POST-STRESSOR DRIVING, results showed an increase in RMSSD between BEFORE and DURING, but not between BEFORE and AFTER. No significant differences were found for the control group. Between group tests revealed further a higher increases in RMSSD for the intervention group compared to the control group, both when comparing BEFORE and DURING and BEFORE and AFTER. Hence, engaging with the intervention induced increases in RMSSD during the post-stressor driving scenario and those effects are sustained for the intervention group after the intervention ceased compared to the control group.

4.1.3 Safety and Performance. To test hypotheses H3 and H4, we followed several steps to process the video data collected during each session. From the CAN bus data, we first eliminated repeated timestamps which accounted for about 49.98% of speed data, 89.95% of binary brake data, and 0% of steering angle data. To smooth the speed data, we applied a 2nd order Butterworth low pass filter with a cutoff frequency of 2 Hz. For the *speed* measure, we further extracted the average velocity (mph) for each segment interval (BEFORE, DURING, AFTER) as well as the last three minutes of the familiarization task as driving baseline. We further calculated the derivative of the filtered speed signals, to average all values taller than zero to generate the *acceleration* measure (m/s^2) for each interval. To make inferences on changes in braking behavior, we used the binary brake data to extract the percentage of time that participants hit the brake (*time on brakes (%))* for each interval. We further calculated the steering reversal rate following the method described in Markkula-Engstrom [14, 28]. To smooth the steering angle data, we applied a 2nd order Butterworth low pass filter with a cutoff frequency of 10 Hz. All steering reversals exceeding a threshold of three degrees were counted for each interval *steering reversal rate* (counts/segment).

With respect to calculating *deviation from the center line* as well as *mild* and *severe lane departures*, we processed the raw video data from each session using OpenCV [5] to extract the lane markers. Due to technical issues, eight sessions suffered problems with the exterior camera system (e.g., a camera falling off during a driving session, camera powering off early), resulting in lost or corrupted data files that made this extraction impossible. For the valid sessions (16), we smoothed the resulting raw data using a Kalman filter [10] to better estimate the position of the vehicle within the lane and address missing data points. Using this processed data, we estimated the number of severe and mild lane departures for each driving interval (Figure 8). We then manually reviewed videos where this analysis indicated there may be a severe lane departure using the forward facing cameras; we also performed this same review for the sessions that did not have exterior camera data.

Driving Safety. We used the entire deceleration signal to look for instances of sudden hard braking events, which is defined at values of approximately 0.6g (~5.88 m/s^2) on dry asphalt [24]. No hard brakes were detected for any participant during the experiment. Further, we detected no severe lane departures for either group.

Driving Performance. To test for changes in driving performance, we first normalized and baseline corrected the data. With respect to the other metrics, comparisons showed no significant differences within the time series nor between the groups for *mild lane departures*, *speed*, *acceleration*, *time on brake*, *steering reversals*, and *deviation from center line*. However, we observed a slight increase in mild lane departures for the intervention group during the intervention. Hence, it seems that the intervention induced minimal changes in participant's normal driving behavior. Our review of the videos and data indicated that these departures were brief and largely occurred during or while executing turns.

4.2 Qualitative Analysis and Results

We analyzed the qualitative results derived from the post-study questionnaire using thematic analysis [4].

4.2.1 The Need for Commute Interventions. Overall, eighty percent of the cohort reported to be either mentally, emotionally, and/or physically *"exhausted"* after a usual workday. Only five participants reported feeling *"nothing of the above"* and reasoned that they *"liked"* what they did or that they *"actively keep a good [work/life] balance"*. Of the affected cohort, seventy-four percent (13/19) clarified that they specifically felt mentally exhausted after work (e.g., *"mostly brain fried."*), while 10% (2/19) expressed physical exhaustion to be present after a workday (e.g., *"tired all over"* from *"walking around all day"*). Four other participants reported feeling *"all of the above"*. Further, eighty-three percent (20/24) of all participants reported mentally processing "negative stress" at work during their commute time. While some participants of this cohort are able to *"debrief"* themselves during the commute, sixty-three percent (15/24) expressed using this time to *"mull it over"* and reported struggling to unwind during their commutes (e.g., *"sometimes there is no unwinding"* and *"I go over any failures at work while driving home."*). Expressed reasons are either because of their *"overanalyzing"* or attributed to the taxing nature of driving (e.g., *"traffic does not allow you to wind down"*). All participants expressed being *"open"* to or needing *"to learn better commute unwinding strategies"*, and some suggested that *"slow and deep breathing is a place to start"*. These findings suggest a need to further investigate and explore the commute as a design space for stress management and health interventions.

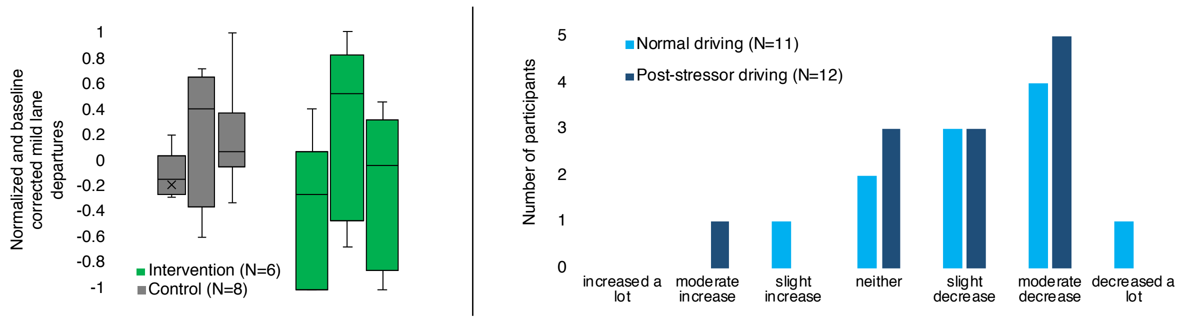

Fig. 9. (*Left*) Boxplots of mild lane departures. (*Right*) Perceived increase or decrease in stress due to intervention for both conditions.

4.2.2 Perceived Beneficial Effects. Overall, participants in the intervention group perceived our haptic guidance intervention as a helpful tool that enabled them to breathe slower in the car (e.g., *"the intervention definitely helped me to breathe slower"*). Participants ranked the guided slow breathing aid, from 0 = "not at all helpful" to 10 = "very helpful", at 6.1±2.6 for the post-stressor condition and 6.3±2.0 for the normal driving condition (with no significance difference). Half of the participants perceived similar effects on breathing rate reduction in both conditions (e.g., *"I tried to keep my inhales at the same slow pace, whether calm or stressed."*). Two participants, however, perceived the intervention as more effective during post-stressor driving compared to normal driving (e.g., *"I didn't slow down as much with it when I was calm"*), while three participants reported experiencing benefits only during the normal driving condition (e.g., *"when I was stressed, the vibrations were just another incoming signal I had to process or ignore."*). The two participants that did not reach the 10% mark in BR reduction also perceived beneficial effects. Notably, both reported to have only engaged with the intervention 32% and 36% of the time compared to a reported level of M = 82%, (SD = 17%) for the rest of the group – consistent with the quantitative analysis which shows slight reductions in HR and increases in RMSSD.

Related to the experienced reduction in breathing pace, the participants overall expressed to have felt calming effects. As Figure 9 indicates, eight participants in the intervention group reported experiencing slight, moderate, or severe decreases in stress during the post-stressor condition and another eight reported slight, moderate, and severe decreases in stress during the normal driving condition. Two participants felt that their stress neither increased nor decreased upon intervention in the post-stress condition and three felt this way in the normal driving condition. One participant was left with the sensation that the intervention led a slight to moderate increase in stress in both conditions. He explained that the swiping sensation was not intuitive for him and that *"if the vibrations were on the left and right shoulder"* he would not have had trouble *"and it would have been relaxing."* Going forward, he expressed needing *"more time to get use to it"* for him to be effective in decreasing BR and benefiting from using the system. In summary, our qualitative analysis estimates that about seventy percent of participants in the intervention group experienced a decrease in stress due to the guided breathing intervention.

4.2.3 Distraction and Safety. Participants rated the intervention's distraction from driving level (*0 = "not at all" to 10 = "very much"*) as mild. We observed an average rating of 3.9±2.9 during the normal driving condition and 3.5±2.8 during post-stressor driving condition with no statistical differences found. Most participants reported that the intervention *"was not distracting"* from the driving task. One participant, however, mentioned that the intervention was *"pretty distracting during the calm condition because it was making me tired"*. Upon the question, whether the intervention would be safe to apply in real traffic (yes/no answer), all participants evaluated the short, breathing intervention as safe to be applied in real traffic (e.g., *"always safe"*, *"no danger I can foresee"*). However, two participants expressed a concern that the intervention could be problematic during calm driving conditions when people are already tired as the intervention could *"make people sleepy"* though neither experienced this themselves. Interestingly, one participant questioned whether the system was functioning properly during the calm driving condition stating *"if it alerts me during calm driving then I would think the system wasn't operating correctly"*.

4.2.4 Future Application. All but one participant (92%) stated they would engage with the in-car guided slow breathing interventions in the future. While most participants would take advantage of the intervention in both normal driving and after a stressful event, three participants expect benefits specifically after stressful events (e.g., *"I think breathing exercises would be more helpful during a stressful event"*, *"to regain calm"*). The participant who expressed the need for more training time with the tool, would rather make use of the intervention during normal driving as he could *"spend more mental energy on it when calm"*. In contrast, one participant expressed her reservation towards future usage (e.g., *"I did not like it."*) and reported being extremely unlikely to use it; however, she did not elaborate.

With respect to specific driving environments, seven participants had no restrictions on when they would prefer to receive the intervention (*e.g., "any time is fine"*). The others prefer to engage with the intervention when waiting at a red traffic light or during highway commutes. Two participants clarified that they would use guided slow breathing *"while being stuck in traffic"*. One participant would even take a break on his commute to engage with the intervention *"at a scenic overview"*. As final remarks, participants see the slow breathing intervention as *"a very positive tool for many due to our current stressful, busy lives"* and as a *"great opportunity to perform a deep breathing daily exercise."*.

5 DISCUSSION AND FUTURE WORK

In this work, we presented the first controlled study of a short, on-road breathing intervention with both calm and stressful driving conditions with a sample of experienced drivers familiar with the regular, daily commuting experience in the US. Our stressor stimulus check confirmed that people were more stressed during the stressor-inducing condition (math task) and that there were no differences in perceived stress between the groups. Moreover, the intervention adoption rate was roughly 82%. For those who engaged with the intervention, the decrease in breathing rate during NORMAL DRIVING was approximately 15% or about one half of the intended decrease. One potential reason for this low percentage is that the baseline BR for two participants decreased throughout the experiment and their BR before the intervention was already at the reduced level. As a result, there were no significant changes within the BR time series or between groups – however the BR measures shows the expected trend. With an increase in RMSSD, we further observe a reduction in arousal between the two groups. Overall, these observations suggest that a system that allows participants to reduce their breathing rate by 30% from their moving baseline value might increase the effectiveness of the intervention though we cannot explicitly confirm prior results in the simulator setup for the calm condition despite observing a favorable reduction [23].

During the POST-STRESSOR DRIVING scenario, participants achieved a 25% decrease in BR which is very close to the target of -30% upon intervention. Our statistical analysis confirmed a decrease in BR upon intervention and this decreases was evident up to three minutes after the intervention ceased. The engagement with the intervention resulted in an increase in RMSSD (i.e., decrease in physiological arousal) and, compared to the control group, a sustained reduction in physiological arousal. Therefore, the intervention was successful in decreasing breathing rate and physiological arousal during the post-stressor driving condition. Although in this paper we used HR as another measurement of stress, it is important to note that HR can be seen as a weaker measurement as compared to HRV (RMSSD). HR can be confounded by exertion including not only physical activity, but also breathing efforts [27]. Therefore the fact that we did not find any effects on HR indicates that both our manipulation and the intervention were successful at exclusively dealing with the effects of psychological stress, i.e., mental stress, which is not due to task performance or other physical demands.

With respect to driving safety, the intervention group did not exhibit any violation in the form of hard brakes or severe lane departure in either driving scenario. This suggests that engagement with the intervention was safe within our context. The analyses of differences in driving performance also revealed no differences. However, there appears to be a slight increase in mild lane departures during the duration of the intervention. While there were only 6 members of the intervention group with full records, a review of all the videos indicated that these minor departures were typically short, lasting only a fraction of a second and usually associated with over correcting during turns. We believe this observation, while important to monitor, would be overcome by users with more time to learn the system.

In contrast to the quantitative findings that demonstrated the effectiveness only for the post-stressor driving condition, qualitative results showed that participants perceived the intervention as being effective in reducing BR and related physiological arousal/stress levels in both conditions. Familiar with the demands of the daily commute, participants rated the intervention as safe to be applied in real traffic—unless the driver is experiencing fatigue or drowsiness. Moreover, the majority of participants imagined engaging with the intervention in the future.

Reflecting on the two participants who statistically did not engage with intervention, we observed that their self-reported level of engagement with the intervention confirmed these findings with values of (M = 34.0%, SD = 2.8%) compared to (M = 81.1%, SD = 16.7%) for the "adoption" group. These participants explained that they "got distracted" by the driving task and did not remember to breath with the haptic feedback. They indicated that more training would be required, and that (*"it would take [them] a while to get used to it to be effective"*). Unsurprisingly, this suggests that some people may find the intervention less intuitive than others.

In summary, and with respect to the research questions stated above, the results of this study demonstrate that (i) the in-car breathing guidance system, as a short duration intervention, lower a drivers' breathing rate and, in turn, arousal levels with sustained effect during post-stressor conditions and—though there are differences in effectiveness of the intervention between normal and stressful driving conditions—user perception of the intervention rate both scenarios as effective; and (ii) that in-car guided breathing interventions can be performed safely within our closed driving circuit with participants agreeing that the experience would be safe for real traffic applications. Our results also indicate that their are numerous opportunities to improve in the design of systems like ours and limitations that should be addressed by additional work in this area.

5.1 Design Recommendations

The aim of this study was to validate the feasibility and efficacy of guided slow breathing interventions in the car. However, in-car guided breathing interventions are still relatively new and there are numerous opportunities for future research. Here, we provide design recommendations for future haptic, in-car systems and describe the need for future research that considers both longitudinal studies and different driving contexts.

5.1.1 Design Recommendations. As a result of our study, future in-car guided breathing interventions that use haptics should consider the following 4 design recommendations. Firstly, provide support for *different vibration patterns* and allow users to select a pattern that is most intuitive for them to follow [3, 23]. Secondly, include a user activated *exploration mode* that allows them to interact with the system before operating the vehicle. Taken together, these two recommendations could be critical to mitigating both adoption as well as safety and performance issues by giving users a chance to learn the system at a pace and style that they are comfortable with. Thirdly, options that allow users to *personalize the strength of the haptic sensations* might also be critical as participants reported variance in their sensory experience. Adding *contextual awareness* was deemed very important by participants with some preferring that the intervention be engaged at, for example, a red light and other preferring to engage on a highway drive or only after a stressful driving event. As a result, creating this feedback loop and determining the best times to intervene during the commute will be a critical area for future research. This is particularly critical as one participant expressed onsets of drowsiness upon intervention during the calm driving condition. Reliable driver state monitoring systems are a must to avoid unfavorable and potentially dangerous effects of breathing interventions. A context-aware system could have, for example, administered a fast breathing intervention instead that has been shown to increase driver arousal [3]. Finally, as some participants reported concern about the system causing drowsiness, it will be important to explore *continuous monitoring* of users physiological signals and driving behaviours to determine how to manipulate the intervention to mitigate this concern or disengage the intervention entirely.

5.1.2 Longitudinal On-road Studies. An appropriate next step for research in this area would also be to validate feasibility of the intervention in multiple real-world scenarios including low and high-traffic conditions as well as urban and rural driving scenarios (similar to prior simulator studies [23]). Moreover, further study is needed to better understand the preferences of commuters, potential benefits of longer intervention durations and/or repeated exposure, novelty effects, and long term health benefits. As a result, longitudinal studies would provide unique and necessary windows into these areas. Finally, as adoption was not 100% in our work, longitudinal studies might also provide an opportunity to investigate barriers to adoption (e.g., the time it takes to learn the system) as well as reasons that people might stop using the system and why.

5.1.3 Contexts. It is also important to note that our research focuses on commuters driving alone to and from their workplace; however, there are numerous other existing and emerging driving contexts that could be explored by future research. For example, in-car haptics might not only be applied to drivers but also passengers and their experiences with and perceptions of using the intervention could be very different. Ride sharing, autonomous cars, and other future driving scenarios (e.g., VR in-the-cars [20]) all offer unique and interesting opportunities to apply in-car haptic interventions for mitigating stress.

5.2 Limitations

It is important to note that there are several limitations of this work. First, our pilot experiments revealed that participants would need to be (i) in an upright body position and (ii) steering with both hands while operating the vehicle to get the best signal from the Zephyr BioHarness. While this is not an unusual position for drivers, it likely differs from their natural body position while commuting. Secondly, our study was conducted in a safe environment (i.e., an empty, underground garage) without traffic. Given that this is the first work to look at an in-car breathing intervention, we believe these conditions were reasonable though it is important to note that driving in the US is a complex activity. Thirdly, we used a hybrid computational+manual approach to assess safety and performance based on our experimental conditions, future studies should continue to evaluate these and other metrics appropriate for scenarios with more complexity and differing safety concerns. Finally, while our participants were experienced commuters, they are not explicitly trained to evaluate safety; however, there perspectives are valuable and encouraging given their experience. In sum, additional experiments and replications should be conducted (including those that investigate the potential for drowsiness) before applying this intervention in a commercial car.

6 CONCLUSION

In this paper, we validated the feasibility and efficacy of in-car guided slow breathing interventions aimed at reducing physiological arousal/stress levels while driving. The intervention adoption rate was about 82%. Those participants who engaged with the intervention reduced their BR and physiological arousal effectively during both conditions though this effect was most prominent in the post-stressor condition. Extensive analysis of driving behavior data showed no violations of driving safety (i.e. hard sudden brakes and severe lane departures) nor critical changes in driving behavior (e.g. speed, acceleration, braking or steering behavior). Despite quantitative results, participants perceived the intervention as being effective in reducing BR and physiological arousal/stress in bother conditions. Participants also rated the intervention as safe to be applied in real traffic – as long as the driver is not already fatigued. The results, overall, suggest that future research in this area should continue with in-traffic testing.

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