Breath Booster! Exploring In-Car, Fast-Paced Breathing Interventions to Enhance Driver Arousal State

Stephanie Balters
School of Medicine
Stanford University
balters@stanford.edu

Elizabeth L. Murnane
Computer Science
Stanford University
emurnane@stanford.edu

James A. Landay
Computer Science
Stanford University
landay@stanford.edu

Pablo E. Paredes
School of Medicine
Stanford University
pparedes@stanford.edu

ABSTRACT

In this paper, we explore the delivery of fast breathing interventions in a driving context, given the proven effects of high-paced breathing on autonomic arousal. Through in-lab simulator studies, we demonstrate the feasibility of using haptic guidance to increase breathing rate, intensity, and heart rate as well as subjective perceptions of alertness and focus. We also assess usability and user receptivity towards the approach across various simulated driving scenarios (highway, city), times of day (day, night), and traffic levels (low, heavy, fast). In doing so, we outline specific use cases where fast breathing interventions are more or less appropriate and beneficial (e.g., during long, monotonous drives on the highway or at night vs. complex or tense driving scenarios), and we offer fertile future directions for the continued development of breathing systems for health and well-being.

Author Keywords

Fast Breathing; Haptic Feedback; Just-In-Time Intervention; Alertness; Arousal; Fatigue; Driving Safety; In-Car Experience.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION

Decreased autonomic activity due to tiredness and drowsiness, task-induced fatigue, and/or boredom has been identified as one of the root causes for road accidents [22], including in autonomous driving conditions [18, 19]. A major breakthrough with respect to road safety could therefore arise from determining interventions that can elicit sympathetic activation in safety-critical scenarios and counteract compromised human states, especially during monotonous, low-stimulus driving contexts (e.g. long highway rides at night with low traffic density).

In this paper, we identify the delivery of fast-paced breathing guidance as a desirable strategy. Our specific contributions are as follows:

- Findings from our proof-of-concept study that demonstrates the feasibility of fast breathing guidance for drivers with respect to both physiological effects and user acceptability.

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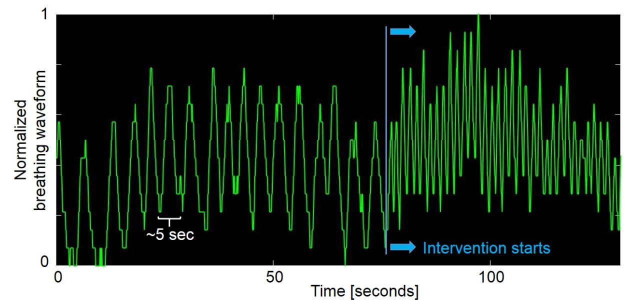

Figure 1. Example data from one participant in our study that illustrates the boost in breathing rate our intervention can elicit.

- A series of design considerations as well as use cases where we identified fast breathing may be particularly beneficial or less suitable depending on driving conditions and driver status.
- A discussion highlighting open challenges and opportunities in the design space of in-car breathing interventions.

RELATED WORK

Fatigue Countermeasures and Interventions

The safety risks of sleepiness (alternatively referred to as drowsiness when felt during the day) and task-induced fatigue are well established [9]. Such problems have been studied for decades in aviation, where standard non-pharmacological strategies for restoring alertness include napping in the cockpit, changing posture or performing mild physical activity, engaging in social interaction, and getting light exposure [8].

In the context of driving, recent questionnaire-based studies have examined how drivers attempt to mitigate fatigue-related impairment, identifying many of the same countermeasures (e.g., stopping to nap or take a walk, performing body movements while driving, and singing or engaging in conversation with passengers), along with other behaviors like turning on the radio, opening the window, and drinking coffee or energy drinks [1] — although the actual impact of these self-reported activities was not measured. Other studies involving controlled experiments have tested some of these approaches. Both coffee and napping have been shown to significantly reduce lane crossing during nighttime driving and improve performance for young and middle-aged adults, but no such difference was observed for self-reported fatigue and sleepiness [29, 36]. Evaluations of the impact of listening to music or opening the window have also been conducted; however, music showed only a modest effect on subjective and objective measures of sleepiness, and opening the window showed no effect [37]. Other work has similarly found that turning on the radio is marginally better at reducing sleepiness than cold air; but again, neither effect was statistically significant in terms of EEG activity, subjective sleepiness, or lane drifts [33].

There is therefore insufficient evidence of the efficacy of these countermeasures in terms of reducing fatigue and sleepiness, increasing vigilance, and improving driving performance. Furthermore, those strategies that have been shown to produce an effect (namely, coffee and napping) come with non-trivial downsides. For instance, consuming caffeine during a nighttime commute home would likely disrupt subsequent sleep quality and quantity as documented by numerous studies [34], even if taken as many as six hours before bedtime [10]. Beyond insomnia, excessive caffeine can also cause headaches, irritability, and nervousness; plus the stimulating, alertness-enhancing effects can be much smaller for those who consume it regularly. Napping can similarly disrupt sleep [5], and pulling over to rest may not be a feasible or safe option for many road conditions [1].

More promising effects have been observed from continuous in-car exposure to blue light, which is known to counteract decrements in vigilance and other neurobehavioral functions [21]. Specifically, blue light has been shown to reduce lane crossing and weaving significantly better than both caffeine and a placebo — however, such effects were observed only in a small study of all males, plus a number of participants complained about the light being blinding, which could also be distracting to other drivers [38]. Further, such bright light exposure is recommended for only occasional use, considering that, like caffeine, it can cause sleep-disruptive or circadian-disruptive effects, especially in the long term [32]. Secondary cognitive tasks (e.g., a free-association verbal task) have also demonstrated efficacy at improving lane keeping and alertness, yet these come with limitations too, as it is likely that they would begin to interfere with attention once the novelty of performing them wears off [2].

Collision avoidance systems are also aimed at mitigating impaired driving performance, in this case through computerized rather than behavior-based approaches. Fatigue-related impairment can manifest as increased lane deviations, fluctuations in speed and steering, and slower response times [43]. Collision avoidance technology can detect such events in order to alert a user of potential collision events [24] or, increasingly, by taking partially or fully autonomous braking and steering actions, although the reliability of such automation is still under debate, and most cars are still not equipped with such technology [12].

Motivated by the open challenge of developing in-car interventions that avoid existing strategies' limitations (e.g., negative short-term side effects, unsafe outcomes from repeated or long-term use, and unclear overall efficacy), we explore an approach involving fast-paced breathing techniques. We were in part inspired by our recent work on passively sensing autonomic arousal in the car [26], and delivering haptic *slow* breathing guidance during driving [25, 27]; those breathing interventions displayed high user receptivity as well as efficacy in terms of producing significant changes in arousal-related physiological measures, without compromising safety.

Physiological Effects of Fast-Paced Breathing

The autonomic nervous system (ANS) is responsible for regulating bodily processes that occur largely unconsciously such as digestion, heart rate, perspiration, respiration, salivation, and so on. The ANS is comprised of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PSNS), which have complementary roles, with the SNS preparing the body for danger or situations requiring quick response ("fight or flight") and the PSNS controlling ordinary functioning ("rest and digest").

Research shows that "fast" or "rapid" breathing modifies a person's autonomic status by reducing vagal tone and activating the SNS [28, 31, 40, 41, 42]. Specifically, these effects have been observed when breathing is performed at a frequency of 1Hz [20] or 2Hz [15] (i.e., a pace of 60 and 120 breaths per minute, respectively) for 1 minute. Breathing has a direct effect on the respiratory sinus arrhythmia (RSA), the natural increase/decrease in heart rate that occurs with inhalation/exhalation, and as such is a known modulator of autonomic arousal [13].

Much of the conversation around the psycho-physiological impacts of fast breathing, including its potential benefits, stems from yoga and its teachings. Yogic fast breathing practices, often referred to as "kapalabhati" or "fire breathing", involve intentional inhalation, retention, and exhalation and are purported to promote focus, increase clarity, and energize the body. Some scientific research has been conducted on such techniques as well, linking them to increased SNS activity [31] as well as reductions in oxidative stress levels and temporary increases in strength [14].

Rapid, patterned breathing also has a history of use during childbirth, given some women report it helps reduce pain [7, 17], though it is unclear whether this is due to distraction or physiological effects on the nervous system. In addition, research on panic disorders has found that voluntary hyperventilation causes consistent increases in sympathetic arousal in people both with and without frequent panic [3]. An increase in sympathetic tone is associated with higher vigilance and attentiveness [23], while decreased sympathetic activity is linked with increased drowsiness [30]. Studies examining vigilant performance with respect to breathing specifically have found that fast-paced breathing can lead to improved performance on a letter cancellation task [41] and a physiological auditory attention task [15].

OBJECTIVES AND RESEARCH QUESTIONS

Altogether, given the known safety risks of fatigue and inattention on the road, the lack of convincing evidence as to the effectiveness and safety of standard countermeasures, and the established links between breathing and SNS activation, we see value in exploring the viability of in-car fast-paced breathing interventions as a means of increasing sympathetic activity and subjective attentiveness. Specifically, we set out to address the following research questions:

1. What are people's attitudes in terms of the intuitiveness and comfort of different rates of faster breathing?

2. Can a haptic system raise breathing rate and SNS activity?

3. How does fast breathing impact a driver's subjective state, and what is the perceived safety of the intervention?

4. Are individuals receptive to using in-car fast-breathing interventions in real life, when, and why or why not?

Figure 2. Driving simulator with vibrotactile seat (left) and while participant is experiencing fast breathing intervention (right).

METHOD

The following subsections provide details about our system for guiding fast breathing, how we piloted it, and the exploratory user study we ran to assess effectiveness and usability. The Stanford Institutional Review Board approved all procedures.

System Setup

As the first exploration of a fast breathing intervention, we conducted a simulator-based rather than on-the-road study so that we could better manage conditions and safety. We used the driving simulator shown in Figure 2, which consisted of a 65-inch curved high-definition screen; driving controls including a steering wheel, pedals, and gear shift; a vibrotactile seat that we described in the next subsection; and a computer running the City Car Driving Software[1]. We used a sedan car with automatic transmission from the simulator portfolio. The software also offered seasonal, weather, and time-of-day settings as well as different driving densities and areas including city, country, highway and track. The seat as well as controllers were adjustable to fit individuals' ergonomics, and the simulator area was shielded with a room divider, as can be seen in Figure 2, to emulate a realistic driving experience. Finally, we used two cameras to capture the side as well as frontal view of participants.

To deliver the intervention, we made use of a haptic vibrotactile seat validated in prior work for its ability to guide breathing patterns [25, 27]. The seat uses forty one 2–3.6 V linear resonant actuator vibration motors that cover a 20x26 inch grid and can produce a variety of different haptic stimulation patterns. We chose a simple pattern that swipes up and down the user's whole back, as participants in prior work found this pattern to be the most acceptable for guiding breathing [25]. The system's control interface allows for the real-time adaptation of the swiping speed to achieve various breathing paces.

Piloting Procedure and Insights

To pilot the system, we recruited a total of 19 participants through convenience sampling in order to gain insights regarding individual attitudes towards fast breathing, reactions to the haptic guidance system, and impressions of driving scenarios where the intervention would be most useful.

To begin, we administered the haptics to 6 participants who drove in the simulator in heavy traffic on the highway during daytime conditions. Following past research on fast breathing [15, 20], we set the intervention length to 1 minute and at a pace 30% above baseline breathing rate, given prior work indicates a 30% change in breathing can produce significant autonomic changes [27]. We found that people had difficulty concentrating on breathing rapidly while driving safely; one participant even crashed the car and attributed it to the distraction of the breathing guidance.

Hypothesizing that fast breathing may be less suitable in demanding driving situations, we ran another 11 participants in the simulator in lower traffic on the highway during daytime. This time, outcomes were promising: a number of people subjectively reported energy-boosting effects, and physiological data showed changes in breathing rate and heart rate as well. Overall, we found that people with a higher baseline breathing rate experienced a greater sensation of increased energy, while those with lower baselines did not perceive the boost. This may indicate that a minimum threshold of fast breathing, in terms of pacing and/or intensity, must be exceeded in order to induce changes in both physiological and perceived arousal.

In addition, participants reported the breathing pattern was intuitive to interpret and follow. Qualitative feedback confirmed scenarios when the intervention would be more or less welcome. For instance, one participant felt fast breathing would help not only when fatigued but also in order to "ready" oneself before critical situations such as fast driving in high-flow traffic; while another reported that fast breathing during highway traffic jams would only escalate the likelihood and intensity of road rage.

Finally, to test such intuitions and inform our next steps, we ran another 2 participants, applying the same +30% baseline fast breathing but this time during actual on-road driving, both on the highway and in the city. Both participants perceived energizing effects from the intervention while reinforcing the importance of identifying appropriate use cases (e.g., similar to the aforementioned simulator participant, one person expressed a preference for using the intervention during "calm" driving, in advance of hitting more complex traffic in order "to get pumped up"), including in scenarios when it would not be problematically distracting (e.g., the other participant missed a highway exit). Still, both felt that the haptic guidance would be safe to deploy.

Exploratory Study

Having established the basic feasibility of our haptic breathing system (i.e., its ability to influence breathing) as well as its basic usability (i.e., users' receptivity and perceptions of the intervention's impact and safety), we moved on to our formal study aimed at more thoroughly exploring various parameters of the intervention including preferred, comfortable, effective, and safe breathing pacing; the impact in different driving scenarios; and overall viability in everyday life.

Participants

We recruited N = 8 participants (2 female, 6 male, 18–34 years old with M = 24.5 and SD = 5.8). All had a valid driver's license and normal or corrected-to-normal eyesight and hearing. The majority of participants (5/8) had no prior experience with fast breathing techniques, while P2 and P4 had taken a class, P5 reported practicing fast breathing every day for singing, and P5 had used breathing apps in the past. All participants had prior experience with haptic stimuli from devices such as smart phones, wearable devices, or massage chairs.

[1]http://citycardriving.com/

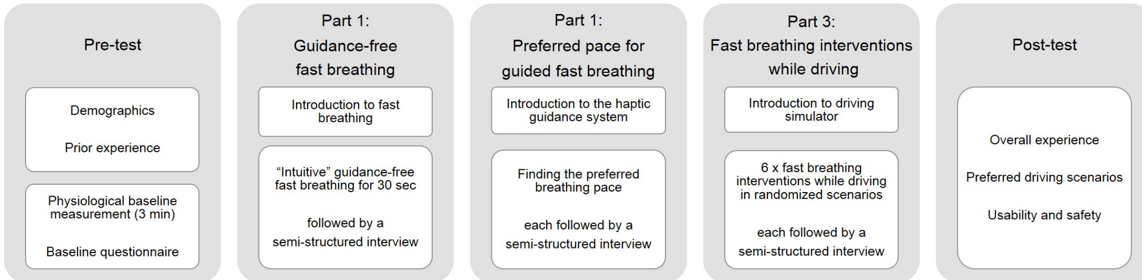

Figure 3. Experimental procedure.

Measures

We used the Zephyr BioModule Device 3.0 to measure breathing pace (1Hz), breathing intensity (18Hz), and ECG (250Hz). The BioModule Bluetooth application was used to access real-time data during the experiment, and data were logged throughout; we manually recorded event markers based on Unix timestamps.

To capture whether fast breathing produced physiological side effects, we familiarized participants with the Simulator Sickness Questionnaire (SSQ) [16], which assesses a variety of symptoms such as headache and dizziness. We also instructed participants to instantly report any symptoms or other physiological impairments experienced at any time during the experiment.

Protocol

The same experimenter (F, 32) ran all participants and used the same equipment setup from the piloting phase. Figure 3 summarizes the experimental procedure.

Pre-test. To begin, participants filled out a questionnaire about demographics and any prior experience with fast breathing, guided breathing, or haptic stimuli. Next, participants were instructed to put on the Zephyr biosensor, sit in the driver's seat, and adjust the seating position. To collect physiological baselines, participants were instructed to stay seated and not talk for the next 3 minutes. Afterwards, we asked participants about their baseline level of energy, concentration and focus, and SSQ symptoms. The simulator was switched off throughout.

Part 1: "Intuitive" guidance-free fast breathing. Next, the experimenter introduced participants to the notion of rapid breathing and then asked them to do "intuitive" fast breathing — that is, breathe at a quick pace that comes naturally in order to energize the body while remaining comfortable. The experimenter moved behind the simulator divider and verbally prompted participants to start and stop this breathing exercise over a period of 30 seconds, which was sufficient to familiarize them with the fast breathing technique and gauge initial reactions. Subsequently, participants were asked to describe their overall experience (e.g., "how did that feel"), changes in arousal (e.g., "did you feel more energized"), and opinions about feasibility and relevance (e.g., "can you imagine doing that in your car").

Part 2: Finding a preferred pace for guided fast breathing. To further gauge acceptability of the intervention and preferences about different breathing paces, the participants were then informed that the car seat contained a haptic guided breathing system and told that the next exercise would be to identify their preferred fast breathing pace to achieve an "energizing yet comfortable" experience. Different breathing paces were tested for 1 minute each, with the goal of maximizing intervention effects by testing upper acceptability thresholds for breathing pace. To allow comparison across participants, we incremented pacing by multiplying personal baseline with a fixed percentage. Participants started with a default pace of baseline x 300% (e.g., a person with a baseline of 12 breaths per minute would receive guidance at a pace of 36). Based on the participant's preference, the pace was then iteratively increased (400%, 500%, etc.) or decreased (200% or 150%) to hone in on an acceptable pace for each participant that felt energizing without inducing discomfort.

In order to test the intuitiveness of the intervention, participants were simply instructed to follow the haptic feedback without explanation of what behavior it was meant to elicit. After each trial, participants were asked about energy, comfort (including SSQ), and overall experience. Finally, at the end of the full session, participants were asked to choose and explain their preferred breathing pace. We also asked whether the haptic guidance was intuitive and if participants would honestly imagine using it for fast breathing in their car in real life.

Part 3: System-guided fast breathing while driving. We then moved on to assess reactions to and impacts of guided fast breathing while driving (in the simulator), using alterations of city vs. highway, daytime (light) vs. nighttime (darkness), and slow heavy traffic (traffic jam) vs. fast heavy traffic vs. low traffic. Figure 4 shows the six resulting conditions: (C1) highway-nighttime-low traffic, (C2) highway-daytime-fast heavy traffic, (C3) highway-daytime-slow heavy traffic, (C4) city-nighttime-low traffic, (C5) city-daytime-fast heavy traffic, and (C6) city-daytime-slow heavy traffic. We chose these scenarios to cover a diverse set of common situations that a driver would encounter and that either prior work, our own intuitions, or pilot findings indicated would be good candidates to test for a fast breathing, autonomic-activating intervention (e.g., C1 might resemble a fatigued commute home with little stimulation while C2 might resemble a morning commute with demanding conditions).

To become familiarized with the driving system and dynamics, participants were introduced to the simulator and given time to take a test drive. Each participant then experienced each of the 6 driving conditions in a randomized order using a Latin square. Each condition lasted 3 to 4 minutes; to avoid anticipation effects, the haptics were randomly administered after 2 to 3 minutes of driving. Participants were instructed to obey all rules of the road, follow the breathing prompts when they occurred, and continue following them for the entirety of their delivery, which

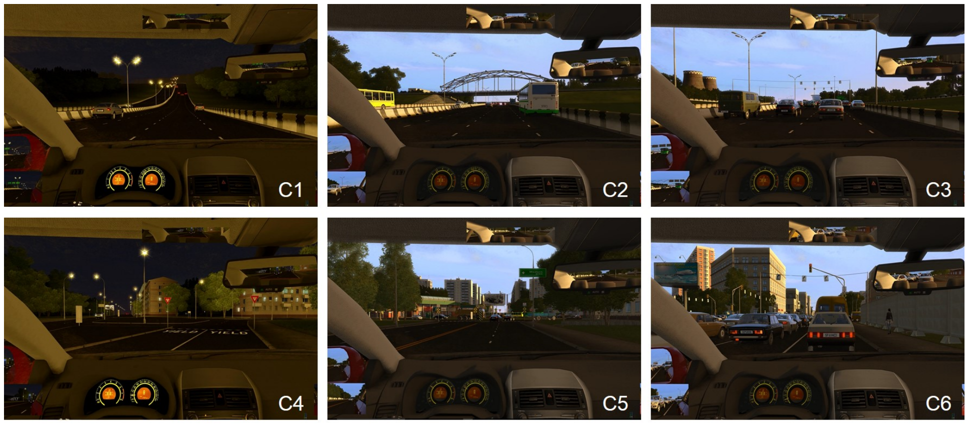

Figure 4. Each participant experienced the fast breathing intervention in all six driving scenarios (C1: highway-nighttime-low traffic, C2: highway-daytime-fast heavy traffic, C3: highway-daytime-slow heavy traffic, C4: city-nighttime-low traffic, C5: city-daytime-fast heavy traffic, and C6: city-daytime-slow heavy traffic), administered in a random order.

lasted 1 minute. Instructions were to follow the course of the highway and to take any desired route in the city. After each drive, we conducted a semi-structured interview with questions about how the intervention affected concentration or focus, perceived changes in energy, any SSQ symptoms, overall experience, thoughts on scenarios in which the intervention would be more or less desirable to receive, and any other feedback.

Post-test. To conclude the experiment, we conducted a semi-structured debrief to explore participants' overall reactions and receptivity, with a particular interest in understanding perceived impacts on energy, focus, performance, and safety as well as opinions on beneficial or inappropriate use cases, both in and beyond the car.

RESULTS

Aiming to obtain key findings that inform the development of fast breathing interventions, we provide statistics describing the physiology data along with qualitative results from our interview and think-aloud data, analyzed using thematic analysis [6].

Physiological Changes and Side Effects

From our physiological data, we computed mean breathing rate (BR) in terms of breaths per minute (BRPM), mean heart rate (HR) using ECG waveform data processed in Kubios [39], and breathing intensity (BI) as the mean amplitude of breathing waveform data (based on changes in pressure sensor data, reported in "bits" [44]). Given pressure sensor data varies according to an individual's breathing mechanism, body composition, and strap tightness [44], we normalized data for each participant and focus on intra-personal analysis. We excluded P5's ECG data due to high noise. Figure 5 illustrates these physiological measures for each participant across each part of the experiment: intuitive (guidance-free) fast breathing, finding a preferred pace for the guided breathing intervention, and driving with the intervention. Note, all participants' BR baseline values fall within a normal resting range (12–18 BRPM [11]; see Figure 5-A).

Regarding the first part of the experiment, we found that guidance-free fast breathing led to different behaviors for different people with respect to baseline (see Figure 5-A, D). For some participants, there was a high increase in BR ($\approx$ 21 BRPM), combined with a medium decrease in BI (by $\approx$ 50%) (P1, P5, P6). For others, we saw somewhat the opposite — a more modest increase in BR ($\approx$ 7 BRPM), with a high increase (by $\approx$ 100%) in BI (P2, P8), medium increase ($\approx$ 50%) in BI (P7), or slight increase ($\approx$ 20%) in BI (P4). One participant even marginally decreased BR ($\approx$ 2.9 BRPM) while maintaining BI (P3). Comparing the BR of each participant across parts 1, 2, and 3, we found the differences to be less than 10 BRPM for everyone except P1 and P7.

When guidance was delivered during driving, the average fast breathing rate across participants was 29.1 $\pm$ 9.4 BRPM (Fig 5-C), with a maximum BR of 46.1 BRPM for P1 (approximately 50% of the 1Hz speed of the fast-paced breathing techniques reviewed earlier [20]). Data showed an increase in HR (3.6 $\pm$ 3.5 BPM ranging from 0.8 to 9.4 BPM) between participants' baseline while driving and when fast breathing while driving (Fig 5-I).

Altogether, these results indicate that the haptic fast breathing intervention was able to induce a significant increase in both breathing rate (delta = 11.31 $\pm$ 6.64 BRPM, $t(7) = 4.82$, $p = .002$) and heart rate (delta = 3.57 $\pm$ 3.64 BPM, $t(7) = 2.73$, $p = .03$). Importantly, our findings confirm the dimensions of breathing rate as well as intensity are influenced by our intervention and should be taken into consideration by future system designs. We also found that there are individual differences in how much a person tends to increase the pacing versus the intensity when prompted to breathe more rapidly. In addition, BR and BI both demonstrated upper limits, which if exceeded, might lead to physical discomfort. At the same time, BR and/or BI must surpass a minimum threshold to elicit sympathetic activation. It remains to be seen what specific range and balance of breathing rate and intensity should be targeted to maximize sympathetic activity.

Regarding any observed side effects, one participant (P2) did report feeling lightheaded after each of the fast breathing segments in parts 1, 2, and 3 and stopped the experiment midway through part 3 due to the lightheadedness. We believe a likely reason may be this participant's considerably higher breathing intensity compared to other participants (see Figure 5-D, E, F); in fact, P2 reported hyperventilating. No other participant reported any SSQ symptoms during the entirety of the experiment.

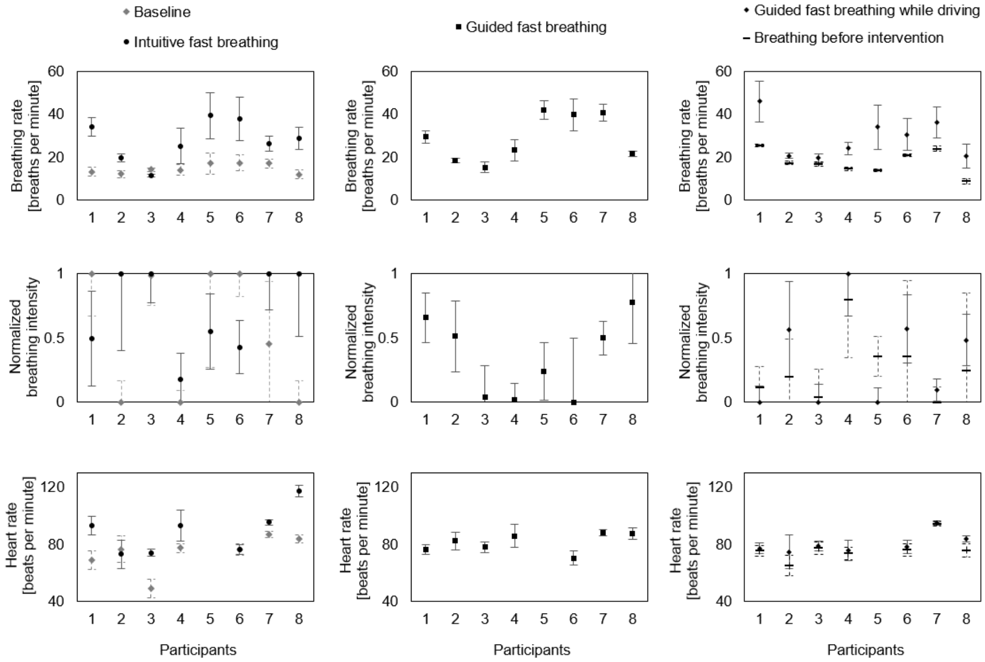

Figure 5. Physiological data were extracted for 5 time durations: (1) physiological baseline period during pre-test (in 5-A, D, G), (2) "intuitive" fast breathing period during part 1 (in 5-A, D, G), (3) individuals' preferred breathing pace period during part 2 (in 5-B, E, H), (4) physiological baseline period while driving in part 3 (1 min before intervention; in 5-C, F, I), and (5) guided fast breathing intervention period during part 3 (in 5-C, F, I).

Qualitative Results

A Balance of Guidance and Control

Half of participants reacted negatively to the guidance-free fast breathing, describing it as *"awkward"* (P8), *"unnatural"* (P1, P8), and/or *"unintuitive"* (P4, P6). The remaining participants were more neutral in their attitudes, though their reactions were still lackluster (e.g., *"It felt okay"* – P5) or noted an absence of any perceived effect (e.g., *"I did not feel anything. It was probably not fast enough."* – P3). At this point, without guidance and while not driving, participants also could not envision fast breathing in the car (e.g., *"I don't think I would have a reason to do so."* – P1) or were outright critical of the idea (e.g., *"No, I would definitely not do it in the car."* – P8).

In contrast, almost all (6/8) of participants responded very positively to the delivery of guided fast breathing, particularly during driving, with four explicitly expressing their desire to receive the intervention in real life (e.g., *"I would love to do it in a real car. Put it into a real car!"* – P5). Importantly, the enthusiasm of responses indicates that participants were genuinely receptive and not merely exhibiting acquiescence bias. Also notable was the fact that two of the participants (P1, P8) who had some of the most negative reactions to the guidance-free fast breathing, actually had the complete opposite take on guided fast breathing in the context of driving (e.g., *"Before, breathing was a bit uncomfortable. Experiencing [the intervention] when driving made me realize its benefit. I started to like it."* – P8).

Still, two participants (P2, P3) were critical of the fast breathing intervention. For P2, the reason was physical discomfort and a feeling of lightheadedness after each bout of fast breathing, while the issue for P3 likely stemmed from an underlying bias against fast breathing due to a mismatch with her own personal routines:

> *"I am a marathon runner, so I train to keep my breathing and heart rate low. I never heard of fast breathing. I would need proof to buy into it."* (P3)

In addition, while the haptic feedback was preferred to a lack of guidance, three participants also expressed a desire to have control over when the feedback would be delivered as well as the autonomy to engage and disengage with the system at will (e.g., *"I would want more agency to switch it on and off myself"* – P6). P1 suggested a start/stop button or an on/off switch. Relatedly, three participants told us that it could be a bit jarring when the intervention would engage and take them by surprise. They told us that a subtle "warning" would be helpful. For instance, P6 suggested a small visual cue, such as a noticeable but non-distracting light that might precede the haptic vibrations. Audio could also be an option, although participants reported preferring haptic guidance alone compared to voice-based cues, which aligns with prior findings on the preferred modality for delivering slow breathing guidance [27].

Perceived Beneficial Effects

For those who reacted well to receiving the intervention, it seems a main reason is that they perceived beneficial effects from performing the fast breathing, particularly due to driving-related advantages. Specifically, the intervention made 6/8 participants felt more *"alert"*, *"energized"*, and/or *"focused"* (e.g., *"My heart beat definitely went up, and I was more alert for sure"* – P4).

In addition to such feelings of invigoration, some participants were left with a sense that the breathing was *"soothing"* and *"pleasurable"* as well, in part because it served as a distraction from stressful thoughts (e.g., *"[When] I am focused on breathing, I don't get annoyed. My anger department in the brain is distracted by the breathing."* – P4), including stress resulting from particular driving circumstances (e.g., *"It distracted me from the annoying traffic"* – P6). It is interesting to note that both of these participants did demonstrate considerable increases in breathing rate during the driving task, with BR increasing from baseline by approximately 66–84%.

These positively charged experiences of activation resonate with The Circumplex Model of Affect [35], which establishes that these two states can exist together, representing high levels on the activation dimension and the valence dimension, respectively. On the other hand, other participants exhibited emotions reflective of high activation and low valence. One such emotion is anger, with traffic jams as a common trigger for participants during our study. For example, P5 and P8 both reported an increase in road rage when performing fast breathing in congested traffic (e.g., *"I got really pissed off. That was road rage... I was already annoyed because of the waiting, and breathing faster increased this feeling."* – P8). Anxiety is another high activation, low valence emotion that some participants link to breathing that surpasses a certain pace (e.g., *"I associate fast breathing above a threshold with anxiety"* – P4).

Altogether, such findings indicate the potential benefits of fast breathing interventions while driving — as long as the driving circumstances (e.g., traffic conditions) and intervention delivery (e.g., breathing pace) are appropriate. Further, such factors may be individually variable, as some participants found the intervention to be a welcome distraction from irritating traffic scenarios, while others felt fast breathing only exacerbated their frustration.

Opportune Driving Scenarios for Intervention

As just mentioned, participants expressed mixed preferences regarding whether traffic jams were a suitable or unsuitable time to perform the intervention, and we identified several other circumstances where it may be more or less appropriate. In particular, driver status and driving scenario appeared to be the two main factors impacting the appropriateness of fast breathing.

Regarding driver status, participants reported that they would welcome the intervention when feeling tired or drowsy on the road in order to feel more alert and energized (e.g., *"I would definitely use fast breathing when I was falling asleep when driving"* – P5), even though we did not tell them that this was a main envisioned use case motivating our work.

In terms of driving scenarios, long drives on boring roads were a preferred time to receive the intervention (e.g., *"When I was on that long stretch of the road I was kind of dozing off. The breathing was good to bring me back, to bring back my focus. There was also a small spike in energy."* – P8). In particular, nighttime driving on the highway precipitated this sort of fatiguing tedium for a number of participants, e.g.:

> *"I felt drowsy during driving on the highway, the dark long drive. Fast breathing re-energized me; I would totally apply it when I am tired on a long drive."* (P5)

Indeed, such monotonous conditions, especially during extended nighttime or freeway driving, are a known cause of task-induced fatigue even when drivers are rested — and low-demand activities have been shown to counteract and improve driving performance in such situations [2]. Our study indicates that fast breathing is one such low-demand activity that can help offset this fatigue and boost alertness.

Distraction and Safety

Delivering a fast breathing intervention during uncomplicated scenarios (e.g., on a straight road) is desirable given that participants typically found it too difficult to manage complex driving situations while simultaneously attending to the fast breathing guidance. We observed that such situations included making turns, switching lanes, accelerating to keep speed with other traffic, and navigating among a large amount of other cars. During such periods of *"decision making"*, as P4 put it, participants were already focused on the driving task at hand (e.g., *"I was already engaged, so I did not need an energy boost."* – P5), which made the intervention feel unnecessary to participants — or worse, distracting.

Overall, all but two participants evaluated guided breathing as safe, as long as not delivered during these inappropriate scenarios. For the two participants (P2, P3) who questioned the intervention's safety, their main concerns related to the level of perceived distraction. For P2, the distraction was due to the previously described physiological discomfort that this participant experienced from the intervention. P3 also associated it with discomfort, both physical as well as psychological, with the latter due to this person's aforementioned resistance towards the notion of fast breathing in the first place.

Beyond distracted driving, we also observed that there may be a risk of fast breathing encouraging somewhat reckless driving behaviors. For example, at one point during C2 (highway - daytime - fast heavy traffic), P4 crashed into a barrier and later explained, *"Due to the breathing I wanted to go faster! Maybe I got too energized."* We similarly observed P7 take a curve too fast during C5 and attribute it to feeling "too energized", although this participant did manage to regain control over the car and avoid an accident. P6 also reported the desire to drive faster due to the breathing intervention.

Such findings suggest that it would be worthwhile for a system to not only have the sensing capability to determine when an individual is becoming fatigued or otherwise in need of the intervention — but to also be able to detect risky driving behaviors like speeding and discontinue the intervention or perhaps reduce the pacing of the breathing feedback, for instance to deliver slow, deep breathing guidance, which prior work has demonstrated can have a calming effect on drivers, including during the sorts of complex, tense situations where fast breathing can be agitating and diverting [27]. In fact, participants expressed a desire for the system to possess other adaptive capabilities as well, for instance to automatically turn on or off at a red light or to last for a duration appropriate for the driver's current circumstances (e.g., *"The intervention was sometimes too long. It should be adaptive in length so that it matches the road conditions."* – P6).

DISCUSSION

In this study, we set out to explore whether fast breathing, which has been associated with sympathetic activation, could be elicited during driving — where a decrease in sympathetic activity (associated with sleepiness and fatigue, including task-induced fatigue from the act of driving itself [30]) — is a serious safety issue and well-recognized challenge to address. Investigating the viability of this approach, we observed that haptic guidance can increase both the rate and intensity of breathing as well as heart rate. Further, all but two participants reported feeling more energized due to the breathing intervention. We also showed that individuals are generally receptive, and in many cases enthusiastic, about using a fast breathing guidance system.

Overall, our findings indicate that fast breathing is a worthwhile design space to pursue, within several constraints we identified related to driver status and driving scenario. Specifically, we found the intervention to be appropriate when drivers may be feeling drowsy, in order to increase alertness, energy, and/or focus, particularly in monotonous driving scenarios known to produce task-induced fatigue. In addition, participants expressed that fast breathing requires attentional resources, which can distract from driving — further making those same monotonous and uncomplicated scenarios an opportune use case for intervention. Our results indicate that fast breathing could be safely applied in these circumstances.

Still, we identified some risks with the intervention and the conditions where it would be less suitable to apply. Specifically, we observed a link between fast breathing and speeding in a few cases, once leading to an accident. We also saw a few instances of road rage when the haptic feedback was administered during a traffic jam, suggesting a connection between breathing and not only activation but also valence. Further, one participant consistently experienced physical discomfort such as lightheadedness, while another was averse toward the experience throughout the study due to a negative preexisting impression of fast breathing.

Design Implications for Breathing-Based Interventions

We envision a context-aware, personalized system that can sense a driver's behavior, physiology, and driving conditions in order to adaptively apply haptic breathing guidance if deemed beneficial, comfortable, and safe. Such adaptivity can handle not only *if* and *when* the intervention is administered but also *how* — i.e., the pacing of breathing, for instance to elicit more rapid and/or intense breathing during a long nighttime drive along a straight empty highway versus slower, more gentle breathing rhythms to calm and compose a driver during a frustrating traffic jam, intricate roads, and other stressful or demanding driving conditions. Indeed, participants expressed a desire for the system to provide this range of breathing speeds (e.g., *"I would integrate different speeds. It would be really cool to have [the system] know how I feel and customize it for me...I would love to have fast breathing and slow breathing...I would definitely use both."* – P4). An evident next step is therefore to integrate the fast breathing approach of this study with the slow breathing in-car interventions validated in prior work by Paredes, et al. [25, 27].

Another is determining breathing "sweet spots". In our study, participants' average guided fast breathing pace was 29.1 $\pm$ 9.4 BRPM with a maximum of 46.1 BRPM. Too rapid and/or intense breathing seemed to produce hyperventilation and lightheadedness and might lead to dizziness or discomfort, including psychological discomfort, as one participant associated anxiety with breathing faster than a certain threshold. On the other hand, slower guidance that did not sufficiently elevate breathing rate did not lead to physiological activation nor any subjectively perceived effects on energy and focus. Our study suggests that the precise values of these thresholds are variable across individuals, warranting further research to better understand such variability as well as the optimal levels and balance of breathing rate and intensity that elicit the greatest sympathetic activation without uncomfortable side effects.

Personalization is also necessary to account for individual differences, as we found that the same driving circumstances and breathing paces could result in different driver reactions. For example, in addition to its energy boosting effects, two participants reported that the intervention produced a mental "awareness" resembling mindfulness that actually helped them stay calm in congested traffic and better manage dense, fast moving driving scenarios. Relatedly, while some users may prefer a system to automatically tailor an intervention's parameters based on current circumstances, others may prefer to manually activate and deactivate, and to tune aspects of the haptic guidance (e.g., vibration speed, pressure, or pattern) in real-time.

Moving Beyond the Car Context

While we focused on driving as a particularly compelling use case, our study allowed us to identify other contexts in which fast breathing would also be valuable and well-received by users.

Apart from P2 (who experienced negative physical side effects), every participant imagined engaging with fast breathing interventions in scenarios beyond driving. Examples included after waking up in the morning to gain energy and prepare oneself for the day or during the workday when experiencing tiredness. Fast breathing guidance was seen as particularly useful in advance of activities where performance is important — be it physical (e.g., exercise or an athletic competition), cognitive (e.g., an interview or presentation), or social (e.g., a romantic date or important work meeting). One participant believed a fast breathing intervention could also provide an emotional boost (e.g., to *"cheer up"* or become more eager). Such observations indicate the potential value of investigating how breathing interventions can influence affect and performance in different scenarios.

Future Work

The scope of this paper was to establish the basic feasibility of in-car fast breathing interventions, in terms of both (1) ability to impact breathing and (2) user receptivity. This goal was served well by a simulator-based lab study, which enabled us to gauge both physiological and qualitative reactions of a previously unevaluated approach in a safe environment and also observe and interview participants in order to identify design constraints.

In the future, it is necessary to undertake road studies in order to confirm whether the effects we observed do hold true during actual driving situations. On-road tests will also make it possible to identify a greater array of real world scenarios (e.g., involving pedestrians, passengers, etc.) that are more or less appropriate for delivering a breathing intervention. Similarly, it will be desirable to engage with larger and more diverse samples (e.g., of various ages, physiological and psychological dispositions, driving experiences and skill levels, typical commuting behaviors, and so on) to make more generalizable claims. Further, it is necessary to establish more robust breathing intensity measures that allow for inter-personal comparison and are particularly applicable in the car context.

Another key next step is to perform controlled experiments that induce fatigue, including in safety-critical scenarios, and test the intervention's impact on driver vigilance (as measured by a validated instrument such as a Psychomotor Vigilance Test) and a quantifiable measure of driving performance (e.g., lane keeping, hard braking) compared to a control condition as well as traditional fatigue countermeasures (e.g., coffee, napping, talking, music, cold air, etc.) the limitations of which we previously reviewed. As part of such research, it would be worthwhile to examine and attempt to increase our fundamental understanding around the neuro-body connection, specifically the mechanisms underlying fast breathing's effect on autonomic status, cortical processes, and task performance.

Field trials deploying our micro-intervention repeatedly over extended periods of time will also be important to assess its long-term effects and adherence; although, based on the literature, we do not anticipate that regularly engaging in fast breathing will produce negative side effects any greater than those associated with caffeine or the other common countermeasures. Future studies can also more closely examine the effects of the intervention in the shorter term, for instance, to measure how long autonomic activity remains elevated after the fast breathing ceases. Related prior work on the sustained effects of slow breathing interventions found that the time to return to baseline could last more than twice as long as the duration of the intervention [27]. In addition, there are also a number of opportunities to explore how interventions could be made not only contextually-aware but also temporally-aware in order to take into account individuals' circadian rhythms and the known time-of-day effects on performance across a variety of tasks [4].

CONCLUSION

This paper demonstrates the feasibility and promise of guided fast breathing interventions to boost sympathetic activation along with subjective energy and focus. In exploring the viability of the approach in terms of both physiological effects as well as usability, we highlighted a number of factors related to both driver status (e.g., boredom, drowsiness, frustration) and driving condition (e.g., traffic, route complexity) important to take into consideration when developing breathing-based interventions. Overall, our work provides a variety of insights and implications for developing breathing-based intervention systems to support physiological performance and psychological well-being.

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REFERENCES

1. Anund, A., Kecklund, G., Peters, B., and Åkerstedt, T. Driver sleepiness and individual differences in preferences for countermeasures. *Journal of Sleep Research 17*, 1 (2008), 16–22.
2. Atchley, P., Chan, M., and Gregersen, S. A strategically timed verbal task improves performance and neurophysiological alertness during fatiguing drives. *Human Factors 56*, 3 (2014), 453–462.
3. Beck, J., and Scott, S. Physiological and symptom responses to hyperventilation: A comparison of frequent and infrequent panickers. *Journal of Psychopathology and Behavioral Assessment 10*, 2 (1988), 117–127.
4. Blake, M. Time of day effects on performance in a range of tasks. *Psychonomic Science 9*, 6 (1967), 349–350.
5. Bonnet, M., and Arand, D. Impact of naps and caffeine on extended nocturnal performance. *Physiology & Behavior 56*, 1 (1994), 103–109.
6. Boyatzis, R. *Transforming qualitative information: Thematic analysis and code development*. Sage, 1998.
7. Brown, S., Douglas, C., and Flood, L. Women's evaluation of intrapartum nonpharmacological pain relief methods used during labor. *The Journal of Perinatal Education 10*, 3 (2001), 1.
8. Caldwell, J., Mallis, M., Caldwell, J., Paul, M., Miller, J., and Neri, D. Fatigue countermeasures in aviation. *Aviation, Space, and Environmental Medicine 80*, 1 (2009), 29–59.
9. Desmond, P., and Hancock, P. Active and passive fatigue states. *Human Factors in Transportation. Stress, Workload, and Fatigue* (2001), 455–465.
10. Drake, C., Roehrs, T., Shambroom, J., and Roth, T. Caffeine effects on sleep taken 0, 3, or 6 hours before going to bed. *Journal of Clinical Sleep Medicine 9*, 11 (2013), 1195.
11. Ganong, W., and Ganong, W. *Review of medical physiology*. Appleton & Lange, 1995.
12. Harper, C., Hendrickson, C., and Samaras, C. Cost and benefit estimates of partially-automated vehicle collision avoidance technologies. *Accident Analysis & Prevention 95* (2016), 104–115.
13. Hirsch, J., and Bishop, B. Respiratory sinus arrhythmia in humans: how breathing pattern modulates heart rate. *American Journal of Physiology-Heart and Circulatory Physiology 241*, 4 (1981), 620–629.
14. Jerath, R., Edry, J., Barnes, V., and Jerath, V. Physiology of long pranayamic breathing: neural respiratory elements may provide a mechanism that explains how slow deep breathing shifts the autonomic nervous system. *Medical Hypotheses 67*, 3 (2006), 566–571.
15. Joshi, M., and Telles, S. A nonrandomized non-naive comparative study of the effects of kapalabhati and breath awareness on event-related potentials in trained yoga practitioners. *The Journal of Alternative and Complementary Medicine 15*, 3 (2009), 281–285.

16. Kennedy, R., Lane, N., Berbaum, K., and Lilienthal, M. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology 3*, 3 (1993), 203–220.

17. Lothian, J. Lamaze breathing. *The Journal of Perinatal Education 20*, 2 (2011), 118–120.

18. Miller, D., Sun, A., Johns, M., Ive, H., Sirkin, D., Aich, S., and Ju, W. Distraction becomes engagement in automated driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 59*, 1 (2015), 1676–1680.

19. Mok, B., Johns, M., Lee, K., Miller, D., Sirkin, D., Ive, P., and Ju, W. Emergency, automation off: unstructured transition timing for distracted drivers of automated vehicles. *Intelligent Transportation Systems* (2015), 2458–2464.

20. Mondal, J., Balakrishnan, R., and Krishnamurthy, M. Regulation of autonomic functions following two high frequency yogic breathing techniques. *TANG 5*, 1 (2015), 19–22.

21. Najjar, R., Wolf, L., Taillard, J., Schlangen, L., Salam, A., Cajochen, C., and Gronfier, C. Chronic artificial blue-enriched white light is an effective countermeasure to delayed circadian phase and neurobehavioral decrements. *PloS One 9*, 7 (2014).

22. National Transportation Safety Board. Evaluation of u.s. department of transportation efforts in the 1990s to address operator fatigue. *Safety Report NTSB/SR-99/01* (1999).

23. Oken, B., Salinsky, M., and Elsas, S. Vigilance, alertness, or sustained attention: physiological basis and measurement. *Clinical Neurophysiology 117*, 9 (2006), 1885–1901.

24. Parasuraman, R.and Hancock, P. Mitigating the adverse effects of workload, stress, and fatigue with adaptive automation. *Performance Under Stress* (2008), 45–57.

25. Paredes, P., Hamdan, N., Clark, D., Cai, C., Ju, W., and Landay, J. Evaluating in-car movements in the design of mindful commute interventions: Exploratory study. *Journal of Medical Internet Research 19*, 12 (2017).

26. Paredes, P. E., Ordonez, F., Ju, W., and Landay, J. A. Fast & Furious: Detecting Stress with a Car Steering Wheel. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2018).

27. Paredes, P. E., Zhou, Y., Hamdan, N. A.-H., Balters, S., Murnane, E., Ju, W., and Landay, J. A. Just breathe: In-car interventions for guided slow breathing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 2*, 1 (2018), 28.

28. Peng, C.-K., Henry, I., Mietus, J., Hausdorff, J., Khalsa, G., Benson, H., and Goldberger, A. Heart rate dynamics during three forms of meditation. *International Journal of Cardiology 95*, 1 (2004), 19–27.

29. Philip, P., Taillard, J., Moore, N., Delord, S., Valtat, C., Sagaspe, P., and Bioulac, B. The effects of coffee and napping on nighttime highway driving. *Ann Intern Med 144* (2006), 785–91.

30. Pressman, M., and Fry, J. Relationship of autonomic nervous system activity to daytime sleepiness and prior sleep. *Sleep 12*, 3 (1989), 239–245.

31. Raghuraj, P., Ramakrishnan, A., Nagendra, H., and Telles, S. Effect of two selected yogic breathing techniques on heart rate variability. *Indian Journal of Physiology and Pharmacology 42* (1998), 467–472.

32. Reiter, R., Tan, D., Korkmaz, A., Erren, T., Piekarski, C., Tamura, H., and Manchester, L. Light at night, chronodisruption, melatonin suppression, and cancer risk: a review. *Critical Reviews in Oncogenesis 13*, 4 (2007).

33. Reyner, L., and Home, J. Evaluation of in-car counter measures to sleepiness: cold air and radio. *Sleep 21*, 1 (1998), 46–51.

34. Roehrs, T., and Roth, T. Caffeine: sleep and daytime sleepiness. *Sleep Medicine Reviews 12*, 2 (2008), 153–162.

35. Russell, J. A circumplex model of affect. *Personality and Social Psychology 39*, 6 (1980), 1161–1178.

36. Sagaspe, P., Taillard, J., Chaumet, G., Moore, N., Bioulac, B., and Philip, P. Aging and nocturnal driving: better with coffee or a nap? a randomized study. *Sleep 30*, 12 (2007), 1808–1813.

37. Schwarz, J., Ingre, M., Fors, C., Anund, A., Kecklund, G., Taillard, J., Philip, P., and Åkerstedt, T. In-car countermeasures open window and music revisited on the real road: popular but hardly effective against driver sleepiness. *Sleep Research 21*, 5 (2012), 595–599.

38. Taillard, J., Capelli, A., Sagaspe, P., Anund, A., Akerstedt, T., and Philip, P. In-car nocturnal blue light exposure improves motorway driving: a randomized controlled trial. *PloS One 7*, 10 (2012), e46750.

39. Tarvainen, M. P., Niskanen, J.-P., Lipponen, J. A., Ranta-Aho, P. O., and Karjalainen, P. A. Kubios HRV–heart rate variability analysis software. *Computer Methods and Programs in Biomedicine 113*, 1 (2014), 210–20.

40. Telles, S., Gupta, R., Singh, N., and Balkrishna, A. A functional near-infrared spectroscopy study of high-frequency yoga breathing compared to breath awareness. *Medical Science Monitor Basic Research 22* (2016), 58.

41. Telles, S., Raghuraj, P., Arankalle, D., and Naveen, K. Immediate effect of high-frequency yoga breathing on attention. *Medknow Publications on Behalf of Indian Journal of Medical Sciences Trust* (2008).

42. Telles, S., Singh, N., and Balkrishna, A. Heart rate variability changes during high frequency yoga breathing and breath awareness. *BioPsychoSocial Medicine 5*, 1 (2011), 4.

43. Thiffault, P., and Bergeron, J. Monotony of road environment and driver fatigue: a simulator study. *Accident Analysis & Prevention 35*, 3 (2003), 381–391.

44. Zephyr. Bioharness 3.0. Accessible from https://www.zephyranywhere.com/media/download/bioharness-log-data-descriptions-07-apr-2016.pdf, 2016. Last accessed April 2018.