# Just Breathe: In-Car Interventions for Guided Slow Breathing

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Motivated by the idea that slow breathing practices could transform the automobile commute from a depleting, mindless activity into a calming, mindful experience, we introduce the first guided slow breathing intervention for drivers. We describe a controlled in-lab experiment ($N$=24) that contrasts the effectiveness and impact of haptic and voice guidance modalities at slowing drivers' breathing pace, which is a known modulator of stress. The experiment was conducted in two simulated driving environments (city, highway) while driving in one of two driving modes (autonomous, manual). Results show that both haptic and voice guidance systems can reduce drivers' breathing rate and provide a sustained post-intervention effect without affecting driving safety. Subjectively, most participants (19/24) preferred the haptic stimuli as they found it more natural to follow, less distracting, and easier to engage and disengage from, compared to the voice stimuli. Finally, while most participants found guided breathing to be a positive experience, a few participants in the autonomous driving condition found slow breathing to be an unusual activity inside the car. In this paper, we discuss such considerations, offer guidelines for designing in-car breathing interventions, and propose future research that extends our work to on-road studies. Altogether, this paper serves as foundational work on guided breathing interventions for automobile drivers.

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

Additional Key Words and Phrases: Deep Breathing, Mindfulness, Stress Management, Autonomous automobiles, Commute, Interventions, Breathing, Health

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Fig. 1. A participant performing slow breathing exercises in the simulated driving setup. A customized haptic seat made of a grid of vibrotactile motors guides her breathing.

## 1 INTRODUCTION

Forty million people spend close to one hour every day commuting by car in the United States alone [U.S. Census Bureau 2009]. Research shows that a lengthy commute takes a toll on psychological health and negatively impacts perceived quality of living [Van Ommeren and Rietveld 2005]. Conversely, framing the commute as a break [Jain and Lyons 2008], or using it as a mental shift between work and home [Lyons and Urry 2005], may have the opposite effect. In essence, transforming the commute into a relaxing experience could potentially counteract the stress[1] accumulated at work and the additional stress encountered during driving.

Current research indicates that it is possible to detect individuals' stress level in cars [Healey and Picard 2005; Hernandez et al. 2014a], which opens up opportunities for intervention. Motivated by evidence that slow breathing is an effective regulator of autonomic arousal [Brown and Gerbarg 2005], we explore its application as a mindful intervention in the car, aimed at reducing stress without impairing driving safety. Our work is the first attempt at designing and studying in-car breathing interventions. Specifically, we test the use of haptic vibrations delivered through the driver's seat (Figure 1) for guiding slow rhythmic breathing and contrast them with conventional voice-guided interventions.

In the remainder of the paper, we discuss the background that informed our design of in-car guided slow breathing interventions and the simulator-based experiences developed to administer them. We then describe our user experiment and present quantitative and qualitative findings in regards to intervention effectiveness, safety, and usability in the car. We close with in-car breathing design guidelines, optimal performance evaluations, and recommendations for road studies.

[1]In this paper we use the term "stress" as a proxy for autonomic arousal.

## 2 PRIOR WORK

In this section, we characterize daily stress, the ways stress can be sensed and managed, and how slow breathing plays a role in stress regulation. We also describe the ways in which guided breathing interventions might impact driving.

### 2.1 Stress Management

Stress affects humans on a regular basis. The development of effective management strategies requires both adequate assessment techniques as well as psycho-physiological knowledge about autonomic arousal and performance.

*2.1.1 Daily Stress and Driving.* The stress response is an evolutionary mechanism that mobilizes physical resources to help humans cope with challenges and life-threatening situations. Acute stress is the short-term response to a challenge (a "stressor") [Lazarus 1966], while chronic stress could be considered as the longer-term response to extreme life experiences and recurring demands [Rabkin and Struening 1976]. In between, we observe daily stress, the day-to-day hassles that repeatedly elevate autonomic arousal and trigger our stress response [McEwen 1998], which has been associated with a variety of pathophysiological risks including cardiovascular diseases and immune deficiencies, impaired quality of life, and shortened life expectancy [Cohen et al. 2007].

Stress, however, is a normal reaction to challenges, and is therefore a much-needed reaction to perform a variety of daily activities, including driving. While the cause of the relationship has yet to be firmly established, the Yerkes-Dodson inverted-U relationship between arousal and performance [Broadhurst, Peter L. 1957] shows that there is an optimal arousal level conducive to higher performance. In other words, too much or too little stress can lead to diminishing results. Regarding the commute, appropriate stress levels might therefore lead to better driving performance [MacLean et al. 2013]; however too much stress (e.g., work stress, which can be exacerbated by additional stress accumulated during the commute [McCrae 1984]) not only does it have a negative impact on mental and physical wellness but it also impairs performance.

*2.1.2 Stress Assessment.* Stress can be measured in various ways, using subjective self-reports or objective physiological signals. One classic self-report questionnaire is the Perceived Stress Scale (PSS) [Roberti et al. 2006], a 10-item inventory where responses to questions about feelings of perceived stress can range from “Low” to “High”. Prior work has demonstrated the validity of single-item measures of stress as well [Elo et al. 2003; Fredriksson-Larsson et al. 2015]. Like most survey-based instruments, multiple reports are required from a respondent in order to establish a personal baseline, which can be used to assess individual changes over time or in order to normalize data and allow comparisons across multiple people.

Stress can be assessed physiologically as well, using sensors placed on or in close proximity to an individual’s body [Burleson and Picard 2004; Healey 2008]. Today, the most typically utilized physiological measures are Electrodermal Activity (EDA), which is also known as Galvanic Skin Response (GSR) and based on electrical properties of the skin, and Heart Rate Variability (HRV) derived from an electrocardiogram (ECG). In recent years, research has also demonstrated that stress levels can be reflected by a number of physical-behavioral signals, including respiration patterns [Wongsuphasawat et al. 2012], movement and muscle tension [Sun et al. 2014], typing pressure [Hernandez et al. 2014b], and prosodic and spectral characteristics of speech [Chang et al. 2011]. Someday, a car might house both these standard as well as more novel stress sensing mechanisms. We focus in this paper on measuring stress through EDA and HRV in order to balance feasibility, granularity, and reliability; and we also capture subjective perceptions through self-report.

*2.1.3 Stress Intervention.* Continuous stress sensing is well-matched to just-in-time (JITI) stress management interventions [Paredes and Chan 2011; Paredes et al. 2014], which aim to deliver personalized, contextually-aware feedback at the right moment. In the car, such interventions can be enhanced using multimodal actuation such as haptics or sound in order to increase engagement and efficacy [Paredes et al. 2015]. Various ideas have been proposed for in-car stress management along these lines such as adaptive music, calming temperatures, and informational dashboards that increase physiological self-awareness [Hernandez et al. 2014a]; however, such interventions remain speculative and have not yet been evaluated.

Furthermore, it is important to consider contextual elements that might mutate what would be an effective intervention into a stressful experience itself. For example, administering an intervention during an inappropriate social scenario or to an individual who does not have the required concentration or time can be awkward, distracting, and fruitless [Laurie and Blandford 2016; Paredes and Chan 2011]. We therefore argue that in-car interventions should be subtle, unobtrusive, and easy to engage and disengage with, as driving conditions and other constraints allow. Considering these identified requirements together with the evidence around controlled breathing and stress reduction described in the following subsection, we pursue an intervention design that promotes slow breathing.

### 2.2 Slow Breathing as a Modulator of Arousal

Breathing plays a fundamental role in regulating the autonomic nervous system (ANS) and reducing autonomic arousal. In particular, breathing has a direct effect in modulating the respiratory sinus arrhythmia (RSA) [Hirsch and Bishop 1981], the natural rhythm in heart rate that occurs during each inhalation-exhalation cycle. In this way, breathing and RSA are coupled with heart rate variability (HRV), a fundamental measure of ANS arousal. HRV is computed as the variation in the interval between consecutive R-R peaks on an electrocardiogram (ECG) signal; this R-R interval is shortened during inspiration and prolonged during expiration. Generally speaking, higher HRV indicates a healthy autonomic and cardiovascular system that can adapt well to stress and experienced demands [Thayer et al. 2010].

Research shows that slow-paced breathing increases HRV and, in turn, leads to concrete stress reduction effects [Brown and Gerbarg 2005; Brown et al. 1993; Van Diest et al. 2014] as compared with optimal-paced breathing which, for the average adult person, is around 17 breaths per minute when at rest [Mead 1963]. The positive impacts of breathing on wellness have long played a role in mental health practice[Benson et al. 1974], and millenarian practices such as yoga, where controlled breathing exercises ("pranayama") are used generate a more focused yet calm state [Brown and Gerbarg 2009; Chong et al. 2011].

Recently, scientific experimentation has shed light on the neural mechanisms behind how breathing affects mindfulness and tranquility. Specifically, research has characterized a tiny cluster of neurons linking breathing, relaxation, attention, excitement and anxiety [Yackle et al. 2017]. A similar group of cells, called preBötC, with similar properties, were already known to exist in mice [Feldman et al. 2012]. Essentially, this group of cells generate a signal that alerts the brain when breathing rate increases. When mice had this group of cells removed, they showed a calm, mellow reaction to environments where their normal counterparts would exhibit a fast sniffing behavior indicative of high arousal.

Despite its direct beneficial impacts, there is some preliminary work in technology-driven interventions that showcase the potential for deep breathing to fail and rather exacerbate stress if not performed properly[Ahmed et al. 2016; Paredes and Chan 2011]. These studies show that some people, with no prior exposure to slow breathing or not properly trained, ended up with higher rather than lower levels of stress.

### 2.3 Driving Safety and Performance

Finally, it is necessary to consider the risks associated with delivering interventions while driving. In particular, despite our intention to create unobtrusive designs, a guided breathing intervention could be a source of distraction, which is a safety concern. At the same time, contextual road conditions (e.g., amount of traffic, pedestrian-dense neighborhoods versus rural roads, etc.) as well as driver proficiency can make different scenarios more or less dangerous for different drivers. It is therefore important to evaluate driving from both objective [Regan and Hallett 2011] and subjective perspectives [Horberry et al. 2006].

Two objective measures associated with driver safety and performance are hard braking (i.e., a fast brake in response to a sudden driving incident [Harbluk et al. 2007]) and lane-keeping (i.e., the deviation from the intended driving lane [Brouwer et al. 1991]). Given the aforementioned situational differences that help determine whether or not certain driving behaviors are dangerous (e.g., the safety risks of lane deviation in dense traffic versus an empty highway), we assess lane-keeping performance both quantitatively as well as through experimenter observation of dangerous violations. We further compare these measures of safety with driver perceptions as part of discussing the feasibility and value in moving towards on-road driving experiments.

## 3 INTERVENTION DESIGN

To explore breathing-based interventions for stress management, we developed two systems that continuously deliver feedback and can be used inside a car. Both methods prompt drivers to inhale/exhale in a manner that achieves a slower breathing rate, with our haptic-based guidance using vibrations and our voice-based guidance providing spoken audio commands.

### 3.1 Haptic Guidance System

In prior exploratory research, we have identified the potential of haptic stimuli as an instructional modality in the automobile, specifically investigating how vibration patterns on the back-rest of the driver's seat can help users perform coordinated movements (configural or breath-based) [Paredes et al. 2017]. This work helped inform our current intervention design by establishing users' ability to interpret vibration patterns, along with their preference for performing slow breathing exercises over energized breathing and sighing. This paper expands upon that work in order to study if and how haptic stimuli can be effectively used to guide slow rhythmic breathing during driving, which we hypothesize can lead to stress reduction and, in turn, improved mental health and overall wellness [Clark et al. 2015].

Our haptic guidance system is composed of forty-one linear resonant actuators (50dB, 13000+/-3000 RPM, 2-3.6V) arranged in a grid (3-inch horizontal spacing and 4-inch vertical spacing to guarantee a clear two-point discrimination [Bickley and Szilagyi 2012; Blumenfeld 2010]). The actuator gird is integrated into the back-rest of the driver's seat and covers an area of about 20in x 26in (see Figure 2). The system provides a continuous vibration pattern that lasts for the duration of one breathing cycle (inspiration and expiration).

During our piloting phase, we designed and evaluated a number of vibration patterns based on metaphors related to cyclic air flow (see Table 1). For example, we tested one pattern wherein the motors begin vibrating from the middle of the seat and then move outwards, like an accordion. Other patterns included the successive vibration of rows going up and down to simulate counting up and down, as well as a spiral with vibrations emanating in spiraling circles. We also tested activating individual vibrotactile motors, columns, and rows in order to examine whether we could deliver feedback to particular locations on the back in a way that would

| **Metaphor/Action** | **Interaction implementation in the car seat vibrotactile matrix** |
|---|---|
| Accordion Open/Close | Symmetric columns vibrating in parallel from the middle column towards the edges or vice-versa. |
| Counting Up/Down | Activate one row per second starting in the bottom row moving towards the top, and vice-versa. |
| Spiraling Outwards/Inwards | Single motors vibrate in sequence spiraling away or towards the center of the matrix. |
| Individual locations | Activate individual rows, columns or single motors that are aligned with the spine, ribs, torso, etc. |
| Air quantity Up/Down | Swipe/massage via smooth overlapping activation of rows with apparent tactile motion [Burtt 1917]. |

Table 1. Early exploration of different breathing haptic guidance patterns inspired in different cyclic air flow metaphors.

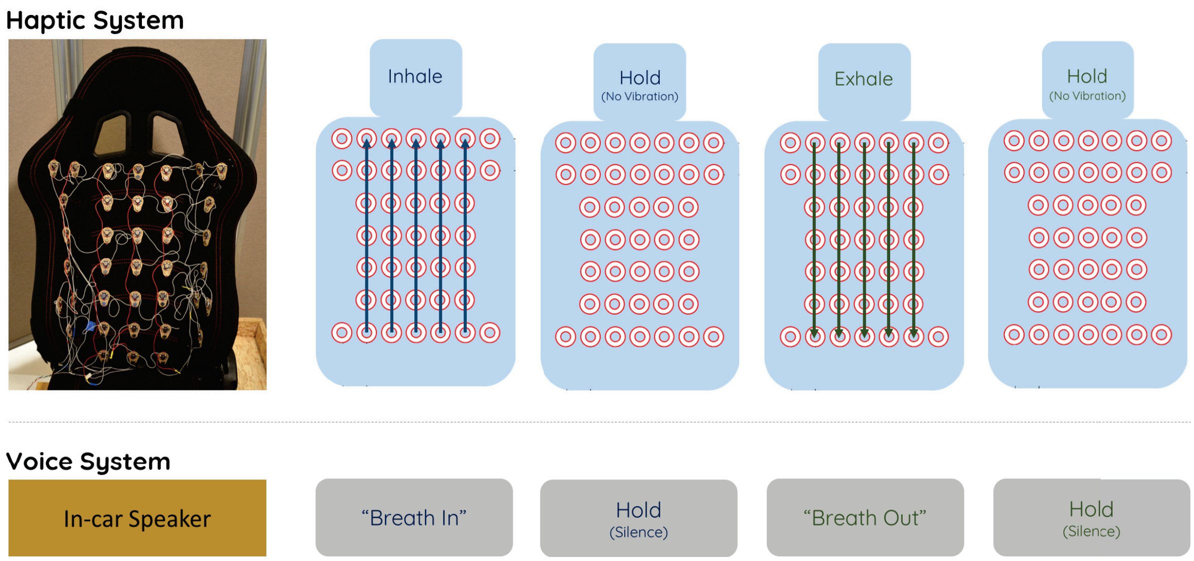



Fig. 2. Intervention design. Top row: Haptic system—car seat back-rest with 41 vibrotactile motors. Guidance patterns: Inhale (swipe up) + Hold (no-vibration) + Exhale (swipe down) + Hold (no-vibration). Bottom row: Voice system—speaker. Guidance pattern: "Breathe in" + Hold (Silence) + "Breathe out" + Hold (Silence).

correspond to the physical movements associated with deep breathing (e.g., spine extension, rib lifting, torso compression, etc.) Finally, after exploring a variety of such patterns with six participants, we concluded that a simple swipe pattern that activates successive rows of motors up and down on a driver's back was the most intuitive, interpretable, and easy for users to follow, as this signal was better correlated with the amount of air in the lungs.

An upward vibration pattern signals "breathe in", a lack of vibration means "hold breath", and a downward vibration pattern signals "breathe out", as shown in Figure 2. Each up—down iteration is equivalent to one breathing cycle with a variable duration that can be adjusted to guide different desired breathing rates. To provide a smooth vibration pattern, we used a haptic technique called Apparent Tactile Motion [Burtt 1917], which recreates the feeling of a continuous "swipe" as adjacent motors are activated with an overlapping window of a few milliseconds [Israr and Poupyrev 2011; Paredes et al. 2015].

### 3.2 Voice Guidance System

Our voice system is based on traditional mindfulness and slow breathing practices that use simple instructions such as "inhale" or "exhale" in order to cue participants to lower their breathing rate [Kabat-Zinn 2003]. To design an intervention along these lines that would utilize the resources of an automobile, we issued voice commands via concealed speakers hidden behind the simulator monitor. We used a speech to text system with a male voice from Apple (Alex Compact) and used Python Audio to control the frequency at which the voice commands were delivered. The system provides two discrete instructions in a given breathing cycle: "breathe in" at the beginning of the cycle and "breathe out" at the middle of the cycle, with silence in between. Again, the duration of this cycle can be adjusted to accommodate different desired breathing rates. In this experiment we chose the same breathing cycle duration for both the haptic and the voice stimuli.

### 3.3 Research Questions

To investigate the feasibility and impact of our slow breathing in-car interventions, we pursued the following research questions:

- R1: Can in-car breathing guidance systems lower a driver's breathing rate and, in turn, arousal levels; and if so, how long does such an effect sustain over time?
- R2: Is there a difference in terms of efficacy and user preference between in-car guided breathing interventions that use haptic versus voice modalities?
- R3: Are in-car guided breathing interventions safe and, if so, would it be safe to test them on the road?

Complementarily, we explored preferences around the potential use of in-car slow breathing guidance systems. In the next section, we describe the experiment we undertook to address these questions.

## 4 METHODOLOGY

Here we describe the details of our in-lab controlled experiment and post-test questionnaire that were designed to evaluate our research questions — i.e., the effectiveness of our haptic and voice-based breathing guidance systems, issues related to driving safety, and participants' preferences and overall receptivity.

### 4.1 Experimental Design

We conducted a controlled experiment with a mixed factorial design to contrast HAPTIC and VOICE guidance systems. The between-subjects factor was DRIVING MODE (AUTONOMOUS, MANUAL). The AUTONOMOUS mode was a level 4, fully automated driving. This factor was used to examine whether the physical act of driving affects how people perceive and respond to breathing guidance. Within-subjects factors included (1) TREATMENT STAGE (BEFORE, DURING, AFTER) in order to observe temporal and sustained effects of the intervention over time, (2) DRIVING ENVIRONMENTS (CITY, HIGHWAY) in order to evaluate the effectiveness of breathing guidance in the most common driving scenarios. The CITY condition represented complex driving situations (e.g., with traffic lights, frequent turn taking, and pedestrians), while the HIGHWAY condition represented less complicated and demanding driving situations. Figure 3 illustrates the decomposition of our independent variables.

In total, we measured twelve dependent variables:

- Physiological stress metrics: *(1) breathing rate, (2) heart rate, (3) heart rate variability (HRV) according to Root Mean Squared Standard Deviation (RMSSD), (4) EDA skin conductance response*
- Subjective stress metric: *(5) perceived stress level*
- Driving safety and performance metrics: *(6) hard braking, (7) severe lane-keeping violations, (8) mild lane-keeping violations, (9) perceived ability to follow guidance, (10) perceived distraction, (11) perceived focus, (12) perceived concentration.*

During the post-test survey we included open-ended questions to examine how often and in what scenarios people would be interested in using a breathing guidance system.

### 4.2 Hypotheses

With this setup in mind, our hypotheses (oriented around R1 and R2) were as follows:

*H1.1: Breathing rate and arousal levels will be lower during intervention as compared to before administration.*
*H1.2: Breathing rate and arousal levels will be lower after the intervention than before it was administered.*
*H2.1: Breathing rate will be lower during autonomous driving than during manual driving.*
*H2.2: Breathing rate will be lower while driving on the highway than in the city.*
*H2.3: Breathing rate will be lower with haptic stimulus than with voice stimulus.*

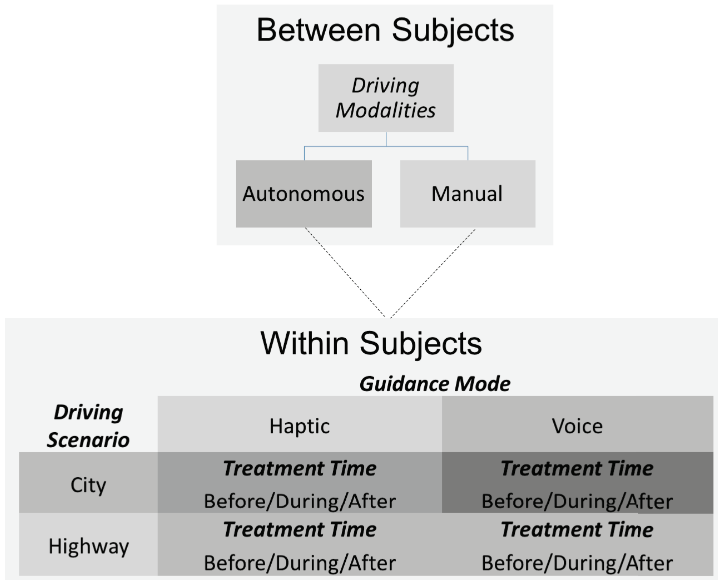



Fig. 3. Experimental design. Between subjects factors: DRIVING MODALITY (AUTONOMOUS, MANUAL). Within subjects factors: GUIDANCE MODE (HAPTIC, VOICE) x DRIVING ENVIRONMENT (CITY, HIGHWAY) x TREATMENT STAGE (BEFORE, DURING, AFTER).

## 4.3 Apparatus and Setup

We ran our experiment using a driving simulator traditionally used to practice for driving tests [City Car Driving 2017] using a standard left-hand driving automatic sedan. The system rendered traffic signs, traffic lights, pedestrians, other drivers with various behaviors, grass, asphalt, sounds, and other realistic environmental elements. We ran the simulator with a curved 4K monitor to give participants a wide view of the road, similar to the front windshield of a regular commercial car. Both the seat and pedals were adjustable to accommodate different body sizes and driving postures. The system was integrated with a two-seater buck to replicate the console and front cabin of a sedan car (see Figure 1). The simulator supported two DRIVING MODALITIES: AUTONOMOUS and MANUAL and two DRIVING ENVIRONMENTS, seen in Figure 4: CITY (complex — where the user interacts with more cars, road signs, pedestrians, turns, etc.) and HIGHWAY (simple).

## 4.4 Data Collection

The experiment was video recorded, and the driving simulation data was stored for future reference.

*4.4.1 Physiological Measurements.* Breathing rate (BR) (1Hz) and electrocardiogram (ECG) (250Hz) data were collected with a Zephyr BioModule Device 3.0 [Medtronics 2012] worn around the chest. BR measurement was based on an algorithm that processed the signal in the frequency domain to guarantee robust estimation. This process introduced an average processing latency of 5 seconds [Aly and Youssef 2016].

For heart rate variability (HRV) calculation, R-peak detection was manually examined following the recommendations of the HRV task force [Camm et al. 1996] using the software Kubios [Tarvainen et al. 2014]. Heart rate (HR) was computed as the average number of beats per minute (BPM) and was correlated with psychological arousal as well as with physical activity. HRV was a second-order metric derived from the reading of an ECG wave and was a proxy for the variability of HR due to the respiratory sinus arrhythmia (RSA). HRV is commonly evaluated in

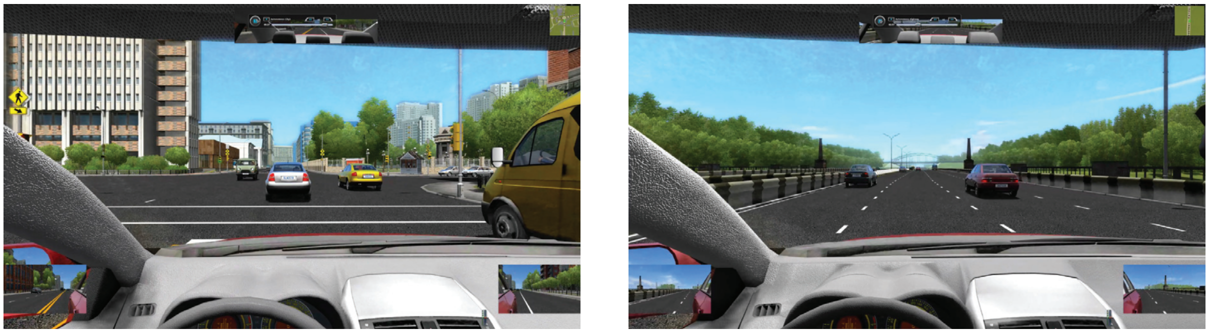


Fig. 4. Driving environments. Left: City (complex condition.) Right: Highway (simple condition).

the time-domain using Root Mean Square of Subsequent Samples (RMSSD) or in the frequency-domain with Low Frequency (LF) and High Frequency (HF) components. RMSSD represents short term variability and is inversely correlated with arousal — i.e., higher levels of RMSSD indicate lower levels of arousal. Some argue that LF/HF is not a good proxy due to the ambiguity of the LF component [Billman 2013]. One instance of this problem arises with slow speed breathing, which shows a dominance of the Parasympathetic Nervous System (PNS) signal in LF, leading to a false positive stress reading [Nunan et al. 2010]. We therefore focus on RMSSD in this study.

Electrodermal Activity (EDA), previously known as Galvanic Skin Response (GSR), is a measurement of skin conductance due to the activation of the eccrine sweat glands, which are purely innervated by the Sympathetic Nervous System (SNS). High average levels and an increased number of EDA peaks have been associated with stress [Boucsein 1992]. EDA (4Hz) was collected with the Empatica E4 bracelet [Empatica 2016], worn on participants' non-dominant hand. The "Event Marking" feature of the Empatica device was used to record time stamps for both devices. First, exponential smoothing (=0.08) was applied to reduce high-frequency artifacts due to motion. Second, each of the sessions were normalized [0,1] [Lykken and Venables 1971] to amplify EDA changes and minimize daily differences due to sensor placement. Next, tonic and phasic EDA components were automatically extracted with the Ledalab library [Benedek and Kaernbach 2011]. Finally, we extracted the average level of the tonic component and the amount of phasic peaks for each part of the experiment, as described further in the Results section. The peaks were extracted with the FINDPEAKS function of MATLAB and were normalized for each session in order to further minimize session differences.

All resulting physiological metrics were max-min normalized [Lykken and Venables 1971] and further corrected against personal baselines to eliminate individual differences, hence their range of [-1,1].

*4.4.2 Self-Reported Stress Measurements.* To capture subjective stress response, we asked participants to use a 10-point scale (1: Low, 10: High) to answer the question: "What is your current level of stress?" before and after each condition block (see Figure 6). Data were max-min normalized [Lykken and Venables 1971] and corrected against personal baselines to eliminate individual differences.

*4.4.3 Driving Safety and Performance Measurements.* To investigate whether the breathing intervention had an effect on (manual) driving safety, we measured *hard brakes*, which counts the number of times a sudden and hard brake sound was elicited from the simulator; and *severe lane-keeping violations*, which counts the number of times the center of the vehicle would touch and/or cross a lane marker on either side. To obtain a preliminary evaluation of performance, we measured *mild lane-keeping violations*, which counts the number of times (at least) one wheel of the vehicle would touch and/or cross a lane marker on either side. All of these measures were derived from the manual driving condition and normalized.

To gain insights into participants' subjective perceptions regarding the GUIDANCE MODALITIES impact of the intervention on driving safety, we inquired about the following in the post-experiment questionnaire: *following commands* ("how often did you follow the guidance modality commands", on a scale of 0% = never to 100% = always), *distraction* ("how distracting were the commands", 0 = not at all to 10 = very much), and *focus* ("how much focus did the guidance require", 0 = not at all to 10 = very much).

We further captured self-reported concentration by asking participants to respond to a 10-point scale (1: Low, 10: High) question: "What is your current level of concentration?" before and after each condition block (as seen in Figure 6). Responses were corrected against personal baselines to eliminate individual differences.

### 4.5 Participants

Twenty-four participants were recruited for the study (12F, 12M) ranging in age from 18 to 64 (M = 29.2, SD = 13.01) years old. All participants possessed a valid driver's license and were compensated with a $25 gift card at the end of the study.

A little more than a third (9/24) reported practicing some form of slow breathing on a daily or weekly basis, while a little less than a third (7/24) reported never practicing it at all. When asked about what activities they engaged in when feeling stressed in the car, the majority of the participants (17/24) preferred to listen to music, others (9/24) reported singing, and the remainder reported various other behaviors such as listening to the news, stretching, opening the windows, or pulling over to rest momentarily.

Notably, only 2/24 participants reported using any guided breathing application on their smartphones, and only 4/24 had used some other form of relaxation app. Regarding prior experiences with haptic interfaces, some participants (10/24) were familiar with haptic smartphone vibrations, 9/24 had used a massage chair, and 10/24 reported never experiencing haptic feedback.

We recruited participants who commute or had commuted by car in the past. Among those, about half (11/24) of participants reported currently commuting by car every day, 6/24 commuted a few days a week, 5/24 commute once a week, and 2/24 participants reported not currently using a car for commuting. 10/24 participants reported having a daily commute of 30 minutes or less, 8/24 reported a daily commute of 30 minutes to an hour, 3/24 reported a daily commute of one to two hours, and one participant had a commute lasting longer than two hours every day.

### 4.6 Procedure and Task

Before beginning the experiment, each participant signed a consent form and answered a short questionnaire about prior experience with breathing technology. Next, the physiological sensors (ECG, breathing rate harness, EDA bracelet) were placed on a participant's body by the experimenter. After the participant finished the pre-survey questionnaire, on average about 10 minutes, the experimenter take the baseline reading for breathing rate (BR) and programmed the guidance systems with a frequency 30% lower than the baseline BR. The experimenter sat behind the car simulator to monitor the participant's breathing rates (see Figure 5).

Participants were assigned to one of two DRIVING MODES (AUTONOMOUS VS. MANUAL). In each condition, participants drove in a DRIVING ENVIRONMENT (CITY VS. HIGHWAY) for six minutes: two minutes without any intervention, followed by two minutes with a breathing GUIDANCE MODALITY (HAPTIC VS. VOICE) counterbalanced across participants and finalizing with two minutes with no breathing treatment (TREATMENT STAGE = (BEFORE, DURING, AFTER)). At the end of the six minutes, participants stopped driving for two minutes to provide self-reported stress and concentration levels (Figure 6). Overall, each participant performed 2 GUIDANCE MODALITIES × 2 DRIVING ENVIRONMENTS = 4 conditions. Following the conditions, participants answered a post-experiment questionnaire that evaluated the effectiveness and distraction generated by the guidance systems. The entire process lasted approximately 30 minutes.

Fig. 5. Experimenter in the back of the buck with participant in the driving seat.

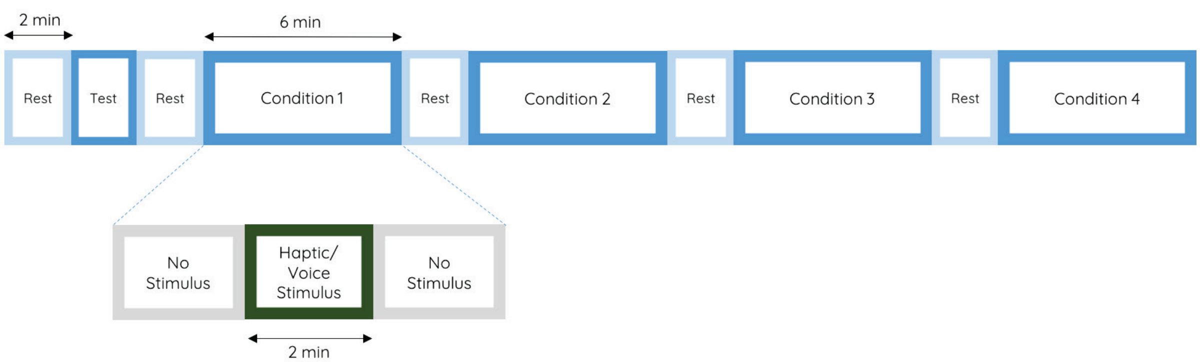



Fig. 6. Experimental timeline for either driving mode condition.

## 5 RESULTS

In this section, we present findings from our quantitative and qualitative analyses of data from our controlled experiment and post-experiment questionnaires.

### 5.1 Quantitative Analysis

*5.1.1 Physiological Data.* We analyzed the normalized and baseline corrected [-1, 1] physiological data using four-factor mixed ANOVAs (DRIVING MODE between-subjects; DRIVING ENVIRONMENT, GUIDANCE MODALITY, and TREATMENT STAGE within-subjects), and we subsequently performed either paired t-tests or one-way repeated measures ANOVAs with Bonferroni correction for post-hoc pairwise comparisons for statistically significant results in the factorial analysis. No assumptions were violated.

*Breathing Rate.* First we validated if our BR manipulation, measured in breaths per minute (BrPM), worked overall. Tdhe difference between BR before (M = 16.471, SD = 3.404) BrPM, and BR during the intervention (M = 11.813, SD = 2.517) BrPM was of 28.283%, which is close to our expected objective of reducing BR by 30%.

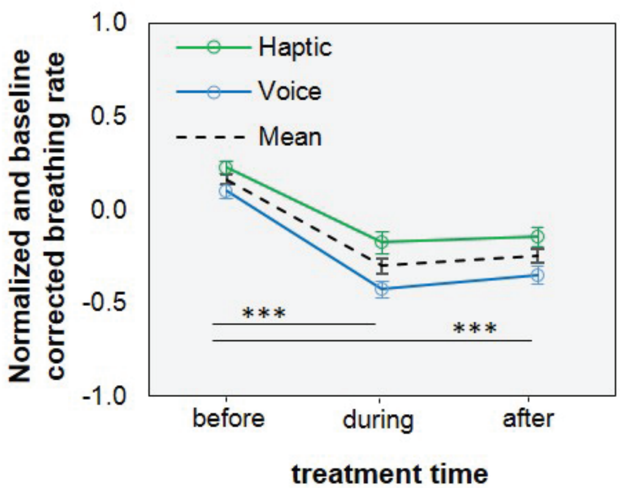
With this assurance, we proceeded to analyze the normalized and baseline corrected BR data. We found significant main effects for GUIDANCE MODALITY (HAPTIC, VOICE) ($F(1,22) = 13.373$, $p < .001$) and TREATMENT STAGE (BEFORE, DURING, AFTER) ($F(2,44) = 82.334$, $p < 0.001$) on *breathing rate*. Post-hoc analysis revealed that there is a significant difference between HAPTIC and VOICE in all the treatment conditions BEFORE ($t(47) = 2.642$, $p < 0.01$), DURING ($t(47) = 3.507$, $p < 0.001$, and AFTER ($t(47) = 2.974$, $p < 0.01$) (see Figure 7a). In order to evaluate the effects relative to the *before* condition we compared two differential treatment metrics between HAPTIC and VOICE: (1) immediate effect (DURING - BEFORE) and sustained effect (AFTER - BEFORE). We found no significant differences, which indicates that both conditions are not different in their effect size. With the total amount of readings, ($N$=96), we can perform an equivalence test with power higher than 0.75 and $\alpha = 0.05$ for a equivalence margin of +/-10% using a two one-sample test method (TOST). Under these assumptions the reduction in breathing rate for HAPTIC and VOICE are not equivalent (90% $C$[0.007, 0.24]). Applying the same TOST test to the sustained effect, we found that these values are equivalent (90% $C$[-0.033, 0.188]). Jointly, these findings mean that although VOICE had a stronger immediate effect, HAPTIC was able to sustain its effect more than VOICE.

Further post-hoc analysis ($F(2,46) = 85.419$, $p < 0.001$) on the aggregate TREATMENT STAGE revealed a significant reduction on *breathing rate* of 50% (95% $CI$[-0.590, -0.337], $p < 0.001$)) between BEFORE ($M = 0.161$, $SD = 0.128$) and DURING ($M = -0.303$, $SD = 0.226$) treatment, as well as a significant reduction of 40% (95% $CI$[-0.496, -0.323], $p < 0.001$)) between BEFORE and AFTER ($M = -0.248$, $SD = 0.169$) treatment. No significant difference was found between DURING and AFTER treatment (see Figure 7a). This immediate sustained effect has been observed in prior studies where participants had the opportunity to practice a slow breathing technique [Sroufe 1971], and also a longer-term sustained effect [Anderson et al. 2010]. In order to estimate the duration of this effect additional post-intervention measurements are needed.

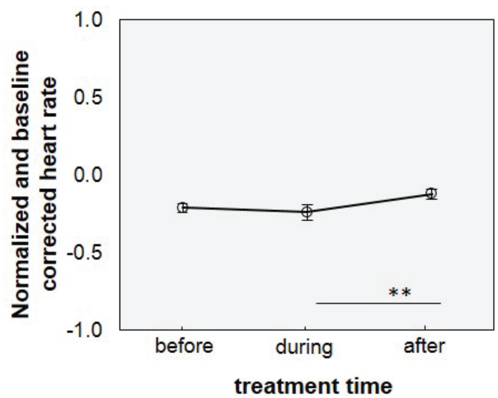
We found no significant difference between any other factors on *breathing rate*. Altogether, our results indicate that both HAPTIC and VOICE guidance can successfully reduce breathing rate and sustain its effects regardless of driving environment, guidance modality or activation.

*Heart rate.* We found a significant main effect of TREATMENT STAGE ($F(2,44) = 4.872$, $p < 0.05$) on participants' average *heart rate*. Post-hoc analysis ($F(2,46) = 4.866$, $p < 0.05$) revealed a significant difference between DURING ($M = -0.240$, $SD = 0.240$) and AFTER ($M = -.120$, $SD = 0.165$) TREATMENT ($p < 0.01$): average beats per minute (BPM) increased by 10% (95% $CI$[0.031, 0.205]). In other words, heart rate rose after breathing guidance stopped being delivered (see Figure 7b). We found no significant main or interaction effects for any factor on *heart rate*.

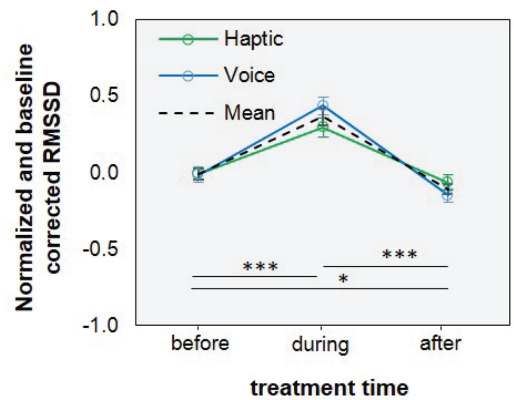
*RMSSD.* As mentioned earlier, we use Root Mean Square of Subsequent Samples (*RMSSD*) to evaluate heart rate variability. RMSSD is inversely correlated with arousal, i.e. higher *RMSSD* is indicative of lower arousal levels and vice versa. We found a significant simple main effect of TREATMENT STAGE ($F(2,44) = 75.115$, $p < 0.001$) on average *RMSSD*. Post-hoc analysis ($F(2,46) = 76.703$, $p < 0.001$) revealed a significant difference between BEFORE ($M = -0.013$, $SD = 0.171$) and DURING ($M = 0.365$, $SD = 0.267$) treatment ($p < 0.001$): average *RMSSD* increased by 40% (95% $CI$ [0.264, 0.492]), a significant difference between DURING and AFTER ($M = -0.108$, $SD = 0.149$) treatment ($p < 0.001$): average heart rate variability decreased by 50% (95% $CI$ [-0.580, -0.366]), and a significant difference between BEFORE and AFTER treatment ($p < 0.05$): *RMSSD* decreased by 10% (95% $CI$ [-0.186, -0.004]) (see Figure 7c). In addition, we found a significant interaction effect between GUIDANCE MODALITY and TREATMENT STAGE ($F(2,44) = 10.201$, $p < 0.001$) on *RMSSD* (see Figure 7c). We found no significant effect or interaction effect of any factor




(a) *Breathing rate* BEFORE, DURING, *and* AFTER *treatment. Both,* HAPTIC *and* VOICE *guidance methods produced a reduction in breathing rate (BR) that sustained beyond the end of treatment delivery.*




(b) *Heart rate (HR)* BEFORE, DURING, *and* AFTER *treatment.*




(c) *Heart rate variability (RMSSD)* BEFORE, DURING, *and* AFTER *treatment.*

Fig. 7. Participants' physiological signals (*breathing rate*, *heart rate*, and *RMSSD*) across different TREATMENT STAGES. Bars in each plot represent standard errors of the means with $p \leq 0.05$ (*), $p \leq 0.01$ (**), and $p \leq 0.001$ (***).

on *RMSSD*. Overall, this means voice-based guidance produced a greater increase in *RMSSD* (i.e., lower arousal levels) during delivery than haptic guidance, although arousal levels then returned back to their levels before treatment. Such findings are in line with a number of prior studies, which find heart rate variability quickly returns to baseline after temporary perturbations (e.g., due to mild exercise) and requires more powerful stimuli (e.g., maximum exercise, extended-release drugs, etc.) to produce more prolonged changes [Camm et al. 1996].

*Electro-dermal Activity (EDA).* We found no significant effect or interaction effect of any factor on *EDA*. We believe this is because EDA is quite sensitive to motion artifacts. That is, even though the measurement device was worn on a participant's non-dominant hand, the act of steering introduced a substantial amount of noise. Such findings suggest EDA may not be the most appropriate metric of arousal for activities that involve movements known to skew results.

### *5.1.2 Driving Safety and Performance.*

*Driving Safety.* For the manual driving condition, we performed factorial analyses (three-way ANOVAs) to evaluate the effect of DRIVING ENVIRONMENT, GUIDANCE MODALITY, and TREATMENT STAGE on each of our safety and performance measures described earlier: hard braking and severe lane-keeping violations, which are indicative of safety problems, and mild lane-keeping violations, which are indicative of performance issues. No assumptions were violated.

For *hard braking*, the factorial analysis revealed no statistically significant effects; and across all conditions, we observed an average of less than one hard brake per participant BEFORE ($M$ = 0.208, $SD$ = 0.544), DURING ($M$ = 0.313, $SD$ = 0.512), or AFTER ($M$ = 0.438, $SD$ = 0.823). Additionally, no *severe lane-keeping violations* were detected during the entire experiment. With the total amount of observations, ($N$=96), we performed an equivalence test with power higher than 0.75 and $\alpha = 0.05$ for a equivalence margin of +/-10% using a two one-sample test method (TOST). We found that the number of hard breaks DURING the intervention is not equivalent to the original baseline (90% $CI$[-0.283, 0.075]), which indicates that there was an increase on the average of hard breaks during the intervention. Furthermore, the number of hard breaks AFTER are also not equivalent to those DURING the intervention (90% $CI$[-0.357, 0.107]). Although statistically speaking we see some differences, it can be viewed from a practical perspective that safety issues were not a problem, with less than one hard break on average per participant per condition, which was further validated through analysis of participants' subjective experience variables related to safety. This information helps answer research question 3 (RQ3), indicating that the safety concerns are minor and that it is reasonable to progress towards more ecologically valid tests (i.e. on-road studies).

*Driving Performance.* Although safety was our priority, we also analyzed *mild lane-keeping violations* to gain a preliminary intuition about the effect that our interventions may have on driving performance. The absolute values for *mild lane-keeping violations* were very low, with means oscillating between zero and two violations per condition (see Figure 8). It is worth noting that Participant 3 is an outlier in almost all driving conditions, i.e., P3's performance issues may well be due to personal driving ability or simulator intolerance. Indeed, in our post-experiment questionnaire, P3 reported that "the simulator makes me feel dizzy, and I cannot drive straight." Analyzing P3's lane-keeping violations specifically, we found that this was the only participant who exhibited violations where more than 20% of the car was outside the lane marker.

A preliminary ANOVA analysis of the min-max normalized *mild lane-keeping violations* revealed main effects of DRIVING ENVIRONMENT ($F(1,11) = 10.247$, $p < 0.01$) and TREATMENT STAGE ($F(2,22) = 17.985$, $p < 0.001$). Regarding DRIVING ENVIRONMENT, mean *mild lane-keeping violations* were 25% (95% $CI$[0.153, 0.357]) higher in the highway condition compared to city condition, as revealed by a paired samples t-test across all highway and all city conditions ($t(71) = 4.977$, $p < 0.001$). This result is not surprising, as the difficulty of lane-keeping is a much better indication of performance in a high speed environment such as the highway, as opposed to a low speed one like the city. Given the amount of readings ($N$=48) per each guidance condition, there is not enough power to perform an equivalence test.

A post-hoc A TOST equivalence analysis of the min-max normalized *mild lane-keeping violations* ($N$=96) with power higher than 0.75 revealed an that BEFORE ($M$ = 0.246, $SD$ = 0.325) and DURING ($M$ = 0.388, $SD$ = 0.365) are not equivalent (90% $CI$[-0.259, -0.025]), which means that *mild lane-keeping violations* during the intervention are

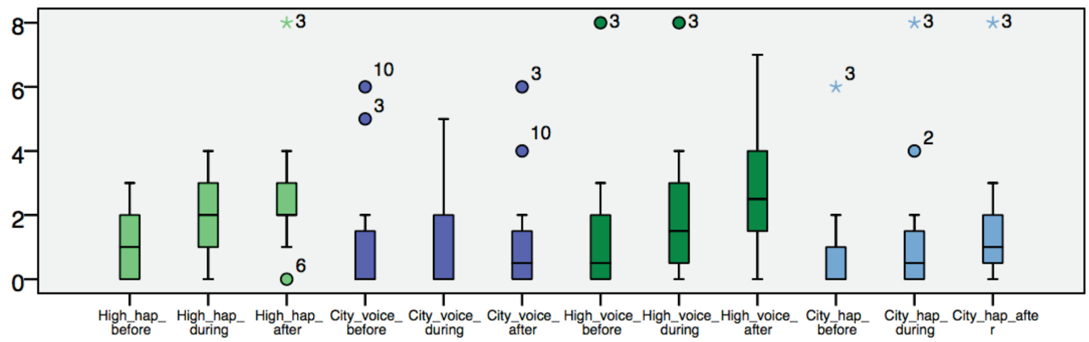



Fig. 8. Box plots of raw lane-keeping violation data before, during, after all driving environment and guidance modality conditions ("High" = Highway, "hap" = haptic). Normalized values were used during statistical analysis.

higher than the baseline. Additionally, DURING and AFTER ($M$ = 0.548, $SD$ = 0.405) are also not equivalent (90% $CI$[-0.259, -0.025]), which indicates that there is a sustained increase of *mild lane-keeping violations* even after the intervention has ended. A careful observation of Figure 8 reveals that *mild lane-keeping violations* increase in every condition over time. This may be due to fatigue or a compounded effect of the intervention and its residual effects, and we speculate that the incidence of lane-keeping violations may similarly rise over the course of a driving episode in everyday life.

While outside the scope of this paper, we see an opportunity for future work to more fully evaluate links between stress and performance, including to investigate whether particular levels of arousal might be stimulated through interventions not unlike our own, in order to reach an optimal level of driving performance. Furthermore, performance would be best evaluated in on-road experiments, including to mitigate simulator-related confounds like those experienced by P3; and our research's findings regarding safety help verify the feasibility of such studies.

#### *5.1.3 Subjective Measures.*

*Subjective Stress Level.* We performed four-factor mixed ANOVAs to evaluate how our experimental conditions affected participants' self-reported *stress level*. No assumptions were violated. While we saw a reduction in subjective stress level from before to after the intervention, differences were non-significant. We imagine this is due to the fact that we did not induce stress as is common in many stress-related experiments (e.g., by administering an acute stressor such as a loud noise, a demanding task, etc. [Hernandez et al. 2014b]), making the perceivable reduction in stress less extreme in our case. Rather, we aimed to more closely replicate a real life commuting scenario in order to test whether our interventions were effective at reducing baseline stress levels.

*Perceived Experience Metrics.* A three factorial two-way mixed ANOVA was performed to understand the effects of DRIVING MODE and GUIDANCE MODALITY on the following metrics of participants' perceived experience: *ability to follow guidance*, *level of distraction*, and *level of required focus*. No assumptions were violated. Regarding *level of distraction*, data showed a single main effect for GUIDANCE MODALITY ($F$(1,22) = 4.417, $p$ < 0.05). To analyze this main effect, we ran a paired-samples t-test for *level of distraction*, which revealed a statistically significant decrease of 1.583 (95% $CI$[0.059, 3.107]) between VOICE and HAPTIC guidance (5.29 ± 2.37 to 3.71 ± 2.50 ($t$(23) = 2.148, $p$ < 0.05) (see Figure 9). This finding, that VOICE was perceived as more distracting than HAPTIC, guidance was corroborated by open-ended responses from our questionnaire, as we describe further in Section 5.2. For *ability to follow guidance* and *level of required focus*, no statistically significant values were found. Such results

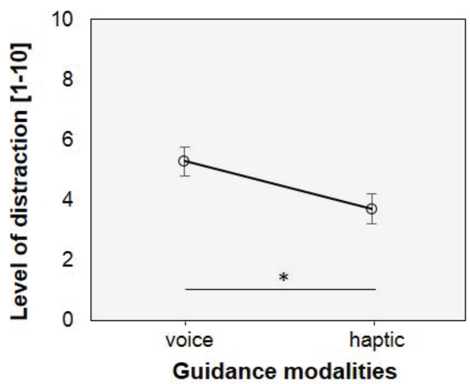



Fig. 9. Level of perceived distraction when given breathing guidance via voice or haptic modalities.

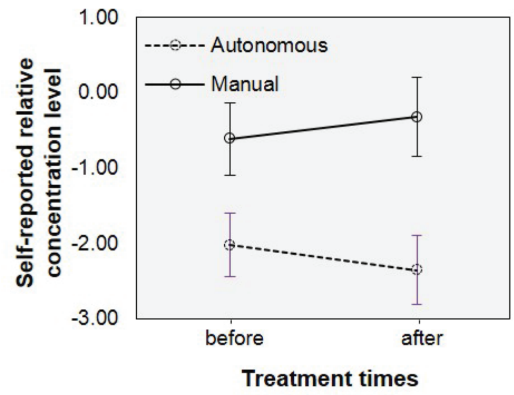



Fig. 10. Perceived concentration level before and after breathing in autonomous and manual driving modes.

could be impacted by the fact, however, that when more complicated traffic scenarios were encountered, some participants simply ignored whatever type of breathing guidance was being delivered.

*Subjective Concentration.* To evaluate how our experimental conditions affected participants' self-reported *concentration*, we performed four-factor mixed ANOVAs. No assumptions were violated. Results showed a significant interaction effect between DRIVING MODE and TREATMENT STAGE ($F(1,21) = 4.756$, $p < 0.05$) on (relative) *concentration*, as seen in Figure 10. The lack of main effects means we cannot define a clear cause, though the fact that manual driving requires more concentration than automated driving seems an intuitive finding.

## 5.2 Usability Analysis and Qualitative Themes

In this section, we provide descriptive statistics and qualitative insights about participants' reactions to the haptic and voice guidance modalities based on their responses to closed- and open-ended questions about perceived usability, subjective preferences, and overall personal experience. We support previous quantitative results and provide information about preferences for future use.

*5.2.1 Easy, Effective, and Pleasing Experiences.* Overall, participants found both forms of breathing guidance very easy to use. Specifically, on a scale of 1-3 (1: hard, 2: moderate, 3: easy), participants rated *ease of use* at a 2.44 ± 0.62, with ratings for each guidance modality very similar: 2.46 ± 0.59 for HAPTIC and 2.42 ± 0.65 for VOICE, with no statistically significant difference between the two guidance modalities observed.

Ratings for the perceived *effectiveness* of both forms of guidance were similarly high: 4.02 ± 1.56 on a scale of 1-5 (1 = very ineffective, 5 = very effective) overall, with 4.17 ± 1.53 for HAPTIC and 3.88 ± 1.67 for VOICE guidance, with no statistically significant difference between the two guidance modalities observed.

Finally, the breathing interventions also fared well in terms of how *pleasing* participants found them to be 3.13 ± 1.66 on a scale of 1-5 (1 = very unpleasant, 5 = very pleasant), with 2.83 ± 1.64 for MANUAL and 3.42 ± 1.68 for AUTONOMOUS driving mode and no statistically significant difference between the two driving modes observed.

*5.2.2 A Preference for Haptic Guidance.* When asked which modality of guidance they preferred, nearly all (19) participants expressed a preference for haptic guidance, while 4 preferred voice-based guidance. A main reason cited was the calm subtlety of the vibrations on their backs compared to the more overt, sometimes even jarring, voice commands — e.g., *"I liked the vibrations better than the voice because the vibrations were more continuous,*

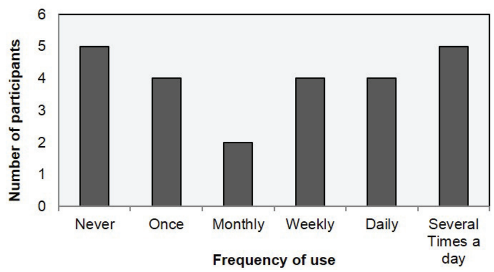



Fig. 11. Expected future frequency of use of a slow breathing haptic guidance system.


Fig. 12. Average rank of preferred contexts in which to receive haptic guidance.

*calm, and flowing, while the voice was sometimes surprising, unexpected, and stood out"* (P21) and *"Vibrations felt more natural and in sync with my body, whereas voice commands were slightly jarring sometimes"* (P14). Relatedly, the "gentleness" of the less "commanding" haptic feedback was appreciated — e.g., *"I didn't like the voice commands - felt authoritative. Vibrations felt relaxing and helped with breathing"* (P20).

Our aforementioned findings are highly encouraging about participants' positive impressions regarding easy, effective, and pleasant use of our breathing interventions. However, considering that response biases can have known impacts (e.g., a participant favorably evaluating a proposed design due to social desirability bias), we asked several indirect questions around reactions and receptivity towards breathing guidance, focusing on the strongly preferred haptic modality. Specifically, when asked about the likelihood of using our haptic intervention in the future, participants reported 4.00 ± 2.15 on a scale from 1-7 (1 = extremely unlikely, 7 = extremely likely) with no statistically significant difference between the two driving modes, indicating their openness to future engagement with a similar system.

Along the same lines, we also asked participants how frequently they felt a haptic breathing guidance system should be activated in the car. Of those in the autonomous driving condition, 4 participants answered daily, 3 answered weekly, and 5 answered never; in the manual driving condition, 5 participants answered daily, 3 answered weekly, and 4 answered never. Figure 11 illustrates these reports, which indicate that nearly two-thirds of participants would be interested in using in-car breathing guidance at least weekly. Those participants who did not identify a personal need for the system, noted that they were already relatively calm people — e.g., *"I already feel that I am usually a relaxed driver, and I don't think I need to decrease my stress levels with a haptic seat on a consistent basis in the future"* (P14).

We also asked participants to rank the context in which they would prefer to experience haptic slow breathing stimulation. As shown in Figure 12 (where 1 = most preferred, 4 = least preferred), participants did express a slight preference for receiving guidance at red lights, followed by on the highway, and then in a parking lot compared to at any time during driving.

*5.2.3 Continuous Guidance and Changing Needs.* Fourteen participants (4 in the autonomous driving condition, 10 in the manual driving condition) perceived the haptic vibrations as a continuous gesture, guiding breathing—inhalation and exhalation. For instance, one participant described a sense of learning how to breathe slowly by following the continual vibrations on his back: *"It feels like the 'moving' vibration gives a guide of how air circulates in the body"* (P26).

The remaining 10 participants perceived the haptic vibrations more as "signals" or "reminders" to breathe slowly, where the first sensation of a vibration was enough to "trigger" slow breaths — e.g., *"I felt I needed to breathe when the vibration was activated"* (P17). One participant noted that such interpretations of the vibrations could

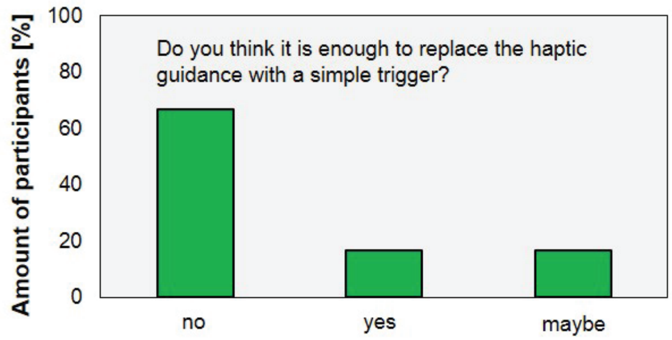



Fig. 13. 66,67% of the participants reported that the haptic deep breathing commands are not replaceable by simple single triggers.

change over time. For this individual, the vibrations served more as a guide at the beginning of the experiment when he was still gaining familiarity with the guidance; but once he learned the patterns and what breathing behaviors they were intended to cue, he started perceiving them more as triggers: *"[They] start as a guide and eventually become a signal"* (P1).

Considering this notion of "learning" or "internalizing" the feedback, we asked participants their thoughts on reducing the vibrations patterns from full, continuous swipe gestures to short, momentary triggers. Most participants (16 — 8 in the autonomous driving condition, 8 in the manual driving condition) did not feel comfortable with the proposition (see Figure 13. Several participants explained that short vibrations would be less effective than continuous feedback because the former could be easily confused with other vibrations experienced as part of normal driving (e.g., the car shaking due to bumpy road conditions). Others thought short triggers could easily go undetected once they become acclimated to them — e.g., *"Trigger is easier to forget when you get used to it"* (P26) or be problematically abrupt and startling — e.g., *"...a single vibration would be jarring and distracting if you weren't expecting it"* (P21). For those participants who did not prefer the haptic modality, a more ongoing versus momentary form of breathing feedback was still preferred; one participant suggested music: *"I would prefer music over a trigger!"* (P15).

Further related to the idea of learning or gaining familiarity with breathing interventions over time was the sense that both guidance modalities eventually became familiar, even if disruptive or distracting at first. For example, *"I really liked it [the vibrating seat] - I found that it was a little distracting to pay attention to the prompts to breathe while concentrating on driving, but I got more used to it after a while, and I think it made the driving experience more enjoyable and relaxing"* (P28). Similarly, other participants noted that they needed time to get used to both haptic and voice based feedback — e.g., *"They are both distracting at first, the vibration was less so. Over time, I became more used to the prompts and found them both less distracting, overall"* (P28).

*5.2.4 Suggested Applications and Improvements.* When asked what improvements they would make to the haptic guidance, several participants suggested giving the user control over the duration and strength of the vibration patterns as well as their distribution over the driver's back. We also received suggestions to utilize the vibration motors to give the driver a massage to further amplify relaxation — e.g., *"Make it [the vibrating chair] more 'massageful'. Use it on other body parts"* (P1). Another participant pointed out that frequent administration of the guidance could lead to adaption and disregard and suggested that perhaps use of the system should be limited in order to preserve novelty.

## 6 DISCUSSION

Our primary goal for this work was to investigate the feasibility, effectiveness, and user reception of guided breathing interventions aimed at in-car use during an individual's regular commute. Focusing on haptic and voice based guidance, our controlled lab experiment demonstrated that both forms of feedback were successful in slowing breathing rate, which has known health benefits particularly when it comes to reducing stress. Further, these positive effects were observed in different types of driving environments (city, highway) and modes (autonomous, manual) and were sustained even after delivery of the intervention ended. Importantly, we found that our interventions did not produce any safety issues, based on both objective and subjective safety metrics.

### 6.1 Implications for Design

In this section, we discuss implications for the design of novel driving interventions that provide engaging, wellness-promoting experiences; and we consider other promising future opportunities, including taking our foundational steps out of the simulator in order to study stress and performance on the road.

*Intervention Duration and Residual Effects.* During the application of our interventions, we found a significant reduction in breathing rate (BR) and an increase in HRV (i.e., a decrease in autonomic arousal). Encouragingly, the post-treatment sustained effects rate for BR reveals a trend already observed in other more elaborate studies [Anderson et al. 2010; Sroufe 1971]. Given that people in the United States spend approximately 25 minutes each way commuting by car, this type of intervention could thus be performed for a few minutes but produce effects that could last for almost the entirety of the commute. Furthermore, our findings indicate that such an intervention could be safely deployed during both city and highway portions of the drive.

The fact that HRV did not have the same recovery pattern, however, begs the question of whether there are other variables modulating this decrease, beyond just breathing rate. In fact, prior literature indicates that BR duty cycle or even the speed at which people inhale or exhale can have significant impacts. Designers should therefore keep in mind that small changes in the administration of an intervention could have residual effects that should be taken into consideration.

*Objective Versus Perceived Efficacy.* The fact that people did not report changes in their subjective levels of stress even though they did experience significant reductions in objective arousal measurements needs to be factored into intervention deployment and adoption strategies. We see two main ways to deal with this mismatch between objective and perceived treatment efficacy. Specifically, interventions could be designed to be either more apparent and overt or in a manner that makes them more subtly disappear into the surrounding environment. This could be achieved, for example, using ambient displays that showcase the personal health gains obtained by the intervention, perhaps using appropriate metaphors to enhance engagement [Consolvo et al. 2008]. The opposite strategy would be to push the intervention to the subliminal or preventative level, for instance, by using novel "mindless computing" paradigms that have shown success in subconsciously regulating physical and psychological aspects of well-being [Adams et al. 2015; Costa et al. 2016].

### 6.2 Ecological Validity, Safety, and Performance

In our study, data showed no evidence that our interventions impaired participants' driving safety or performance. Participants reported that they were able to engage and disengage from an intervention as needed, for instance by simply ignoring the delivered guidance when driving complexity was high. On average, participants agreed that haptic guidance was less distracting than voice, with some reporting that voice was particularly difficult to follow when driving in the city. Driving mode could play a role here as well considering that despite a lack of main effects, we saw a significant a crossover effect between autonomous and manual driving conditions on participants' concentration levels. This raises a question for future work to better understand how guided breathing interventions operate when switching from autonomous to manual driving and vice-versa.

Interestingly, autonomous driving, which compared to manual driving requires low cognitive demands and therefore imposes minimal safety hazards due to human error, was in fact not exempt of risks in our study. In particular, while relaxing in an autonomous car might be beneficial for the mind, there is a risk inherent to partially autonomous systems whereby it might be important for the driver to remain awake and alert in case a manual takeover is necessary in the case of a crisis. Indeed, prior work has observed that it is necessary to balance rest with attention in autonomous driving conditions by creating engaging activities that help prevent drivers from falling asleep [Miller et al. 2015]. Designers therefore must carefully define the driving scenarios during which slow breathing guidance can be safely administered. Furthermore, although both of our breathing guidance modalities managed to significantly lower individuals' breathing rate, participants overwhelmingly preferred the haptic modality, in part due to its soothing nature — but also because it was perceived as easier to stop using when driving attention was required. This finding suggests that enabling users to easily engage, disengage, and reengage with an intervention is an important safety feature.

The fact that we found no effect of our breathing interventions on participants' driving safety in the simulated driving environment is highly encouraging and indicates the merit in moving towards increasingly ecologically valid studies. Participants' aforementioned ability to engage and disengage with guidance as necessary indicates that they feel in control of these intervention systems, but it is important to evaluate whether individuals are similarly able to safely ignore feedback when full attention is required in real-life, on-road driving scenarios. In addition, the simulator environment itself could potentially affect driving performance, as demonstrated by the fact that one participant felt dizzy and was an outlier when it came to lane-keeping ability, further motivating the move to on-road studies and broader metrics of performance beyond hard-braking and lane-keeping (e.g., average speed, following distance, hard-steering, and so on).

### 6.3 Future Work

As the first research to explore in-car interventions for improving commuters' well-being via slow breathing exercises, we have opened up a variety of directions for future work.

*On-road studies.* Our research was performed in a laboratory driving simulator without a motion base. We expect that vibration and noise from an actual driving environment (roads, traffic, radio, passengers, etc.) would impact driver perception of both our haptic and voice based interventions. Going forward, a top priority is replicating our experiment in the wild — first in a closed circuit environment, and later on open roads with traffic. Such on-road studies will additionally help identify situations where drivers respond best to breathing interventions; our participants indicated that red-light stops, traffic jams, parking lots, and highways would be optimal scenarios for receiving stimuli, so future work would do well to begin with these contexts.

*Other guidance modalities.* Given the scope of this paper, we focused on how haptic and voice guidance can be used to effectively and safely slow drivers' breathing rate in an automobile. A desirable next step is investigating the delivery, psycho-physiological impact, and user perception of other stimuli patterns and multi-modal interventions, such as light, heat, pressure, air flow, and sound, just to name a few examples. A key outcome of such work is the discovery of appropriate sensory stimuli that are subtle yet powerful [Adams et al. 2015]. An increased understanding of the effects of such feedback on drivers would allow the design of a collection of interventions that could be dynamically triggered based on a driver's context, performance, and physiological responses. A related compelling topic to consider is that of activation mechanisms — that is, how to begin and conclude a breathing intervention (e.g., two traditional options are explicit user input and contextual activation). We see value in investigating how to personalize these parameters in order to deliver optimal guidance with minimal cognitive distraction. Furthermore, designing a suite of interventions that take into consideration novelty effects could help overcome habituation in order to maintain motivation and adherence over the long term [Paredes et al. 2014]. Beyond slow breathing, which this paper focused on due to its demonstrated health benefits related to stress, technology could also assist in training users to perform other breathing sequences associated with other desirable outcomes of interest, such as fast-paced breathing exercises to increase arousal or attention and combat fatigue [Sakakibara and Hayano 1996]. Similarly, other in-car interventions, such as mindfulness practices [Paredes et al. 2017], are a sensible complement to breathing guidance systems.

## 7 CONCLUSION

In this paper, we introduced a first-of-its-kind in-car intervention system aimed at reducing stress through guided slow breathing. We demonstrated that both haptic and voice based stimuli can be used to successfully reduce drivers' breathing rate and level of arousal. In addition, we measured a sustained impact of our intervention on breathing rate that endured after the stimuli ended. Importantly, neither the haptic nor voice modality impaired safety and driving performance. Subjectively speaking, drivers preferred haptic over voice-based guidance for two main reasons: (1) haptic vibration patterns were perceived as less obtrusive as well as more relaxing than voice commands and (2) continuous haptic feedback, in comparison to discrete voice messages, helped maintain a rhythmic breathing pace. Overall, our work demonstrates the promise of this novel form of intervention in helping users transform their daily driving time into a mindful experience that can reduce stress and increase psychological wellness.

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