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AmbientBreath: Unobtrusive Just-in-time Breathing Intervention Using Multi-sensory Stimulation and its Evaluation in a Car Simulator

JINMO LEE*, MIT Media Lab and Hyundai Motor Company
NESKA ELHAOUIJ*, MIT Media Lab
ROSALIND PICARD, MIT Media Lab

To promote calm breathing inside a car, we designed a just-in-time breathing intervention stimulated by multi-sensory feedback and evaluated its efficacy in a driving simulator. Efficacy was measured via reduction in breathing rate as well as by user acceptance and driving safety measures. Drivers were first exposed to demonstrations of three kinds of ambient feedback designed to stimulate a goal breathing rate: (1) auditory (rhythmic background noise), (2) synchronized modulation of wind (dashboard fans modulating air pointed toward the driver) together with auditory, or (3) synchronized visual (ambient lights) together with auditory. After choosing one preference from these three, each driver engaged in a challenging driving task in a car simulator, where the ambient stimulation was triggered when their breathing exceeded a goal rate adapted to their personal baseline. Two user studies were conducted in a car simulator involving respectively 23 and 31 participants. The studies include both manual and autonomous driving scenarios to evaluate drivers' engagement in the intervention under different cognitive loads. The most frequently selected stimulation was the combined auditory and wind modalities. Measures of changes in breathing rate show that the participants were able to successfully engage in the breathing intervention; however, several factors from the driving context appear to have an impact on when the intervention is or is not effective.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; *Ubiquitous and mobile computing*; **Auditory feedback**; **User studies**; **Displays and imagers**; *Haptic devices*; **User centered design**; • **Applied computing** → Health informatics.

Additional Key Words and Phrases: Breathing Guide, multi-sensory Feedback, Closed-loop Interventions, Ambient Display, Simulated Driving, User's Involvement, Personalization, Automotive, Autonomous and Manual Driving Modes

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1 INTRODUCTION

The complexity of driving includes many stressors, for example, traffic congestion, unsafe behaviors of other drivers or pedestrians, and unexpected situations from mechanical failures or driving mistakes [58]. The stress itself impairs decision-making capability [4], induces high mental cognitive load [71], and results in the negative mood [26]. Driving under stress further increases the chance of traffic violations and crashes [3, 9, 61]. Accumulated

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*Both authors contributed equally to this research.

Authors' addresses: Jinmo Lee, jinmo@media.mit.edu, MIT Media Lab, 75 Amherst St., Cambridge, Massachusetts, 02139 , Hyundai Motor Company, 12 Heolleung-ro, Seoul, 06797; Neska Elhaouij, neska@media.mit.edu, MIT Media Lab, 75 Amherst St., Cambridge, Massachusetts, 02139; Rosalind Picard, picard@media.mit.edu, MIT Media Lab, 75 Amherst St., Cambridge, Massachusetts, 02139.

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short-term stress over daily driving tasks can lead to chronic stress, which contributes to cardiovascular problems [5], gastrointestinal and musculoskeletal disorders [29], and post-traumatic stress [13, 16]. Interventions that reduce stress while driving may thus provide broad health benefits.

Among various efforts to develop an in-car stress management method, breathing interventions have been recently emerging as potentially effective solutions. Breathing allows voluntary regulation of its own rate and has long been used as a method for controlling affective state. The benefit of mindful breathing control has been demonstrated for patient populations suffering from somatic disorders [28], psychiatric disorders [17], and post-traumatic disorder [51], as well as for healthy individuals for improving their attentiveness and stress tolerance [17]. While conventional breathing regulation requires full attention to its process, an in-car breathing intervention requires extra consideration not to distract a driver from their core driving task. Extra demand coming from engagement to a breathing intervention can arouse safety issues of increased infractions and crashes [8] especially by less experienced drivers [75]. At the same time, a completely subconscious and effortless breathing intervention that is safe, may also not be engaged with by the driver, so it may not lower their breathing rate [75].

Note that it is also possible to impact calmness, and potentially heart rate and heart-rate variability, through a heart-rate biofeedback wrist-worn device [19, 20], which provides a desired (usually slower) beating signal through tactile stimulations. We do not explore that approach here for two reasons: (1) We wanted a system integrated into the ambient car environment, and (2) In a car, care must be taken to not overlap a beat frequency with other main vehicle signals, such as the turn signal, which flashes blinks at rates between 60 to 120 times a minute, as required by US and UN regulations [1, 2].

In this work, we implement and evaluate a closed-loop in-car breathing intervention system using ambient multi-sensory stimulations aiming for an adaptive breathing regulation of a driver. The present closed-loop system consists of wearable sensors for monitoring the physiological signal for the driver, breathing intervention devices for multi-sensory stimulations, and a PC controller for a driver state adaptive operation of the intervention. We deployed subtle modulatory signals of auditory, visual, and wind (tactile + thermoceptive) stimuli into the breathing intervention with the goal of lowering the driver's breathing rate while providing minimal distraction. An intervention is considered efficacious if it 1) produces a high engagement level as measured by changing breathing rate, 2) is accepted by the users, and 3) does not alter the driving performance, so that safety is maintained. These measures of efficacy are examined through two user studies in a car simulator. In both studies, the comprehensive analysis of the breathing intervention is assessed systematically by varying combinations of sensory stimuli, manual and autonomous driving conditions, and user involvement.

This work makes the following contributions:

- We proposed and implemented combinations of three implicit breathing control methods for a driver using ambient multi-sensory stimulations that exploit modalities present in existing cars: auditory, visual, and wind (thermoception + tactile) feedback.
- We examined the efficacy of the proposed breathing control method in a simulated driving condition and evaluated it under multiple user involvement situations (intervention selection and training) and two different driving task automation (manual and autonomous).
- We found that the users report a higher level of subjective pleasure for a driving task when given a chance to select the intervention types rather than experiencing a random type of intervention.
- We found that the present implicit intervention effectively controls the user's breathing rate by providing an intervention training session, but not without this brief training. It did not change self-reported focus and cognitive load when compared to a control task of driving without the intervention.
- We observed a higher level of the subconscious breathing engagement of drivers to the intervention under autonomous driving compared to manual driving.

2 RELATED WORK

2.1 In-car Stress Sensing and Breathing Intervention

Bodily responses to stress include changes in physiological signals related to the autonomic nervous system such as heart rate, skin impedance, respiration, muscle activity, and skin temperature [18]. Such multi-modal physiology was first used for automating driver stress recognition in the pioneering work of Healey and Picard [32] where levels of electrodermal activity (EDA), reflecting sympathetic nervous system arousal, were shown to be correlated with levels of driver stress during real world driving conditions. The appropriate passive capture of physiology provides useful information about the timing and severity of a driver's stress without interfering with the driving task [30, 32].

The capability of continuous collection of driver's states enables the development of in-car driver assistant applications for counteracting stress and for enhancing speedy recovery from its impaired mental status [6, 7, 53, 75]. For example, Van Der Zwaag et al. [67] evaluated the effect of negative and positive music on improving a driver's mood and physiology. They found both types of music slowed down the breathing rate of a driver compared to a case of not listening to music. An intervention explicitly targeting a driver's breathing rate was introduced by Paredes et al. [53] in their study using a car simulator equipped with two different types of breathing intervention schemes, haptic feedback in a car seat, and auditory guide using a voice command. In their study, they showed that a driver could regulate his or her breathing rate effectively by engaging with the breathing intervention signals while maintaining safe driving performance. A comparable effect of using an in-car breathing intervention was observed from an on-road test using haptic stimuli installed in a driver's seat [7]. While that study had the advantage of not being in a simulator, it did restrict the route to repeating a short loop of driving within a closed garage setting, where there were no other cars, pedestrians, or bicyclists on the route, making the environment highly controlled and predictable, unlike the open road.

The driving task presents a wide range of cognitive load depending on the complexity and uncertainty in the driving environment, as well as the driver's internal state and driving ability. Mehler et al. [49] reported that the single task of highway driving itself induces a considerable amount of workload, which is equivalent to the 2-back test. Therefore, a secondary task of breathing practices in a car may cause unwanted driving mistakes by adding extra workload beyond the cognitive capacity of a driver. Zepf et al. [75] collected data showing higher accident rates (in a car simulator) when trying to engage a driver consciously with an auditory breathing guide in their study. In their work, the conscious auditory intervention showed both the effects of slowing down breathing rate as well as of increasing driving mistakes during urban driving conditions with medium traffic. The chance of increased driving mistakes under complex driving situations is also reported in the study of Balters et al. [8].

The autonomous mode can be considered an ideal setting to test any in-car intervention's efficacy since the driving task, which is a complex one, is suppressed. Vehicle driving is a task that involves extreme fluctuations in mental workload [21]. The empirical review by de Winter et *al.* [23] presents the noticeable reduction of the perceived workload by the automation of the driving tasks. They collected NASA Task Load Index (TLX) or Rating Scale Mental Effort (RSME) data from 32 simulator and on-road studies regarding the perceived workload under the different driving task automation levels. The average workload levels from manual driving, adaptive cruise control (ACC), and highly automated driving (HAD) were 43.5%, 38.6%, and 22.7%, respectively, from 100 percent as a maximum workload perceived by a driver. Parades et al. [53] tested an in-car breathing intervention for both manual and autonomous driving scenarios in their simulator study. However, their explicit breathing guides already achieved the target breathing rate closely during manual driving, and a significant difference in breathing rate was not observed in the autonomous driving scenario.

2.2 Ambient Display and Multi-sensory Stimulation

The ambient display is designed to convey information through a subtle change in one's environment, without significantly distracting attention from one's central focus [56]. In vehicles, the ambient display is often deployed to bring driving-relevant information to a driver using subtle lighting signals, such as future situations demanding speed reduction [41], messages assisting lane change decisions [45], and driving task take-over requests from an automated driver [14].

Zepf et al. [75] adopted into the car simulator an ambient breathing intervention from Ghandeharioun and Picard [27], which utilized subtle modulatory changes of ambient background white noise to match a desired goal breathing rate. While the technique worked in an office deployment study, in the car (under much higher stress conditions), it did not usually succeed in helping the drivers lower their breathing rates. While the drivers were on average able to maintain regular driving performance under the subtle auditory intervention signal, the effect of breathing regulation showed a non-significant difference compared to a control condition without the intervention.

Multi-sensory ambient stimulation may provide a better way to engage drivers in secondary information while maintaining the primary driving task. Motivated by the Multiple Resource Model [72–74], var Erp et al. [68] investigated the feasibility of a multi-sensory navigation display in reducing both workload and the reaction time to navigation messages. The Multiple Resource Model provides a theoretical background on concurrent processing of multiple tasks with minimal interference across those tasks by decomposing the sensory channels on each. The application of both visual and tactile displays showed a highly reduced reaction time to follow the navigation message. Because of the concern of visual overload during driving [62], Ho et al. [34] assessed a non-visual collision warning system combining auditory and vibrotactile stimuli. Throughout the user study in a simulated driving environment, they reported a significant reduction of braking response time from an audio-tactile warning compared to unisensory alerts of vibrotactile or auditory feedback. However, the use of multi-sensory stimulation appears to be underexplored for in-car stress management. Hernandez et al. [33] suggested multiple solutions of in-car stress management using adaptive music, calming temperature, emotion reflective color changes in dashboard lighting, and so on. However, any synergistic effect of such interventions has yet to be verified through qualitative or quantitative analysis.

The therapeutic effect provided by multi-sensory environments is based on a theoretical framework having two components: automatic reinforcement and the relaxation response. Automatic reinforcement occurs when a person's behaviour creates a favourable outcome without the involvement of another person [63, 69]. The relaxation response is defined as *"a natural innate protective mechanism which allows us to turn off harmful effects from stress through changes that decrease heart rate, lower metabolism, decrease rate of breathing, and in this way bring the body back into a healthier balance"* [12]. Our proposed intervention and study thus focus on multi-sensory ways to automatically assist in decreasing a high breathing rate of the driver, without increasing cognitive load or stress. In our study we will also examine the case when we give participants a choice of using their preferred sensory intervention, not only for purely sensory-preference reasons, but also because having a sense of control over one's environment generally contributes to reducing stress.

2.3 User-centered Design of Automotive HMI

The design of the Human-Machine Interface (HMI) in the automotive field has changed from technology-centered approaches to human-centered or user-centered approaches. The human-centered design process consists of understanding the context of use and specifying user requirements first, concept design second, and concept assessment at the end (ISO 9241-210:2010).

The benefits of user involvement in HMI design have been proven by many studies and can be summarized in five main points [57] by: 1) Improved system quality due to more accurate user requirements, 2) Avoidance of costly system features that the user did not want or cannot use, 3) Improved system acceptance, 4) More effective use due to a better understanding of the system and 5) Increased participation in decision-making.

Different methodologies for human-centered design exist and depend on the user's involvement throughout the design process. Three main levels of involvement are considered: design for users, design with users, and design by users [24]. In the work in this paper, we use the design by users.

User involvement can be informative or consultative for the processes of design for and with users [10]. In the case of an informative involvement, the users are considered a source of information for the early analysis steps in the design process (e.g., surveys, user studies). Then, the designers take over for the concept design and assessment steps. Alternatively, the users participate in the two first steps, namely: analysis and design concept, in the case of a consultative involvement. With participative involvement (design by users), users participate in three steps of the HMI design process with a direct and active contribution to the concept design phase [60]. This type of user involvement helps to improve the efficacy of the HMI by accessing drivers' tacit knowledge and considering their mental models and preferences [25].

According to Francois et al. [25], the success or the efficacy of the HMI can be measured in terms of usability (engagement in our case), distraction, or diversion of attention from the driving task (driving safety), and acceptance.

In this work, we want to present a multi-sensory in-car interface reflecting a breathing intervention designed to help the drivers with calm breathing. The design of the in-car HMI is based on participative involvement of the users by first considering the results and feedback of drivers from a previous work [75]. We further involve users in design through their physiological feedback as a trigger of the intervention and by finally conducting a user study for the assessment of the efficacy of the intervention. The user study conducted and described in this paper considers another level of user's involvement by giving them selection choice over the multi-sensory ambient feedback and by training them about ways to engage with the intervention. In fact, the user's training (demonstrations of feedback systems and discussion) provides a relevant learning opportunity before being asked to make a decision and drive using the interface [22].

3 HYPOTHESES

The present work aims to gain insights about the design of a closed-loop in-car intervention for calming down a driver's breathing rate while not interfering with their safe driving. Placing a higher priority on safe driving, we deployed the ambient form of the breathing intervention using a subtle change of auditory, visual, tactile, and thermoceptive sensory signals surrounding a driver. Our two studies evaluate the following five hypotheses.

- `Hypothesis H0`: Sensory feedback (uni- and multi-) designed to subconsciously "guide" calm breathing inside the car helps to reduce the drivers' breathing rate.
- `Hypothesis H1`: The uninstructed implicit breathing guide by the subtle sensory stimulation allows the driver to maintain safe driving behavior without arousing undesired distraction.
- `Hypothesis H2`: Multi-sensory intervention enhances the unconscious engagement of the driver's physiology to the subtle intervention signal better than the unisensory intervention.
- `Hypothesis H3`: Asking an action of selecting the preferred type of breathing interventions increases the chance of driver's engagement with the intervention.
- `Hypothesis H4`: Automation of the driving task greatly reduces the drivers' cognitive load and enhances their awareness of engaging in the breathing intervention.
- `Hypothesis H5`: Once the driver trains enough to use the intervention, he/she will engage in the breathing intervention better while being distracted more from the driving task by consciously being aware of the breathing. The unobtrusive stimulation design of the intervention will minimize this side effect of distraction within an allowable range of safe driving.

4 SYSTEM DESIGN

4.1 Simulated Driving Environment

Fig. 1. The SIMUMAK car simulator and the sample images of simulated driving scenes

We deployed the simulated driving environment for the user study-based verification of the closed-loop breathing intervention system. The car simulator used in the present study is the single-driver SIMESCAR SILVER driving simulator, manufactured by SIMUMAK. This simulator is equipped with the essential driving components, such as steering wheel, three foot-pedals (gas, brake, and clutch), 6-level gear shift (5 gears + reverse), front light indicators, horn, windshield wipers, and safety seatbelt. In emulating the realistic driving experience, the simulator shows the driving scenes on three connected 32” monitors surrounding a driver and provides 2-DOF longitudinal and lateral seat movement corresponding to the acceleration, braking, and steering motions. The simulator’s driving history data is automatically logged in secured storage providing quantitative data of telemetry and the number of driving mistakes. For verification of `Hypothesis H4`, we customized the simulator to provide an autonomous driving experience to the study participant. The present autonomous driving experience was enabled by the remote control of the simulator using the digital driving controller set (G29, manufactured by Logitech) and 55 inches full HD LCD screen, which were connected to the main controller PC of the simulator through USB serial and HDMI port, respectively. We enclosed the front and two sides of the simulator, and the remote control unit was not exposed to any of the participants before and during the user study. An experienced instructor operated the remote control of the simulator in the emulation of the autonomous mode. Thus, it was driven by a human, but the participant thought it was driven autonomously.

4.2 Closed-loop System

In the present study, we developed the closed-loop breathing intervention system with three types of sensory stimulations; auditory, visual, and wind (tactile + thermoceptive) stimulations. As shown in Fig. 2, the closed-loop system consisted of sensing, control, and intervention modules.

For sensing the physiological signal during the driving task, we asked the driver to wear the Zephyr BioHarness chest strap [37, 38] and the Affectiva Q-sensor wristband [55]. The Zephyr sensor was used to capture the breathing and heart rate at 1 Hz sampling frequency. The Q-sensor was applied to monitor the EDA and skin temperature at 8 Hz sampling frequency.

The collected physiological data were stored in the controller laptop in real-time, and the MATLAB version of the control logic decided the intervention operation mode between the modulation ON and OFF by comparing

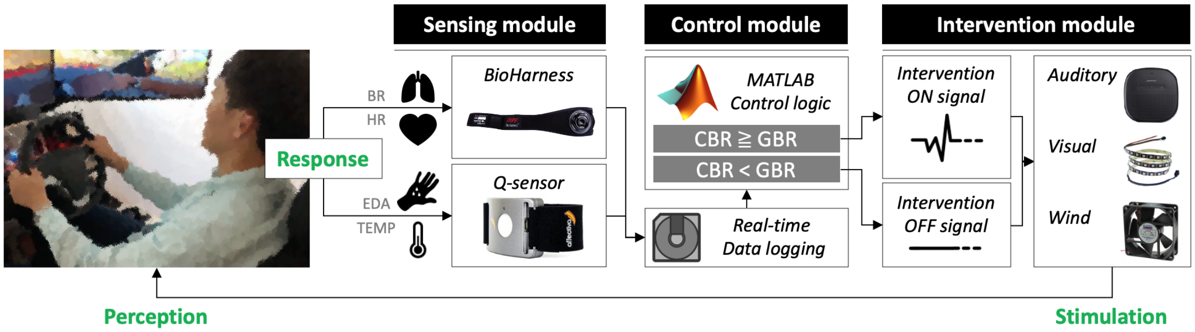
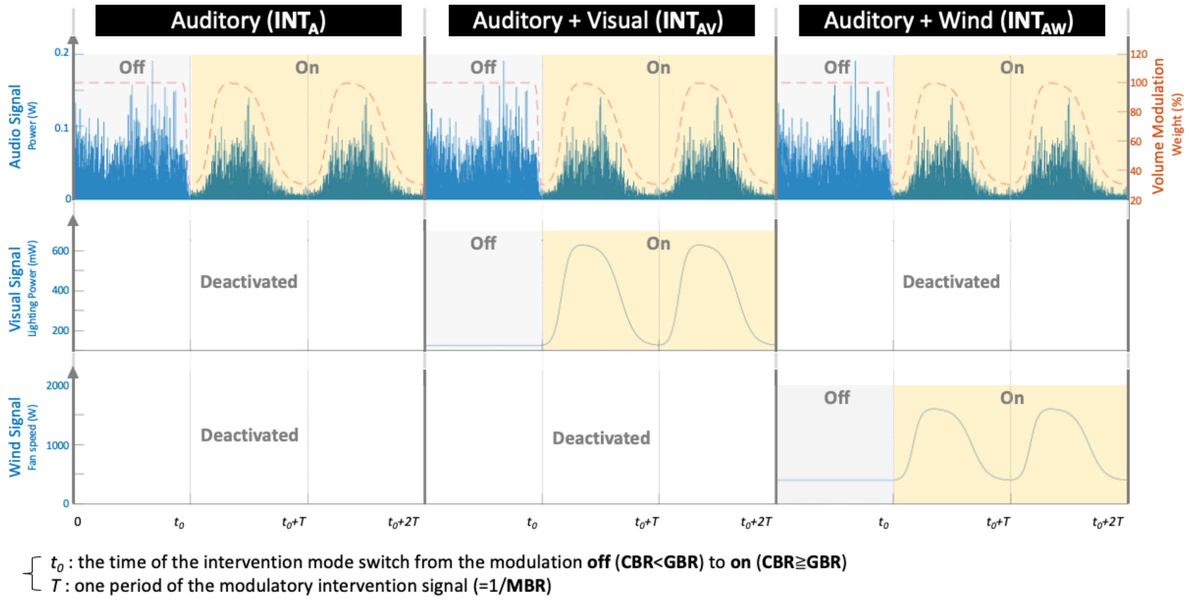


Fig. 2. Description of the closed-loop breathing intervention system

the current breathing rate (**CBR**) and the goal breathing rate (**GBR**). Whenever **CBR** was equal or greater than **GBR**, the closed-loop system turned on the modulation of the sensory stimulations' intensity. Otherwise, when **CBR** was lower than **GBR**, the system turned off the modulation. The **GBR** was customized for each driver by setting its value at 120% of the mean-breathing rate (**MBR**). The **MBR** was the breathing rate of a driver during the rest period in the simulator without any task. We intended to locate this GBR value between the breathing rate under non-demanding activity and the normal driving task based on the given values from the former studies [7, 75]. Zepf et al. [75] showed the normalized breathing rate of 1.3 under the simulated driving task without a breathing guide. Based on the denominator of their normalization (goal breathing rate), this value corresponds to a 55% higher breathing rate compared to the baseline breathing rate measured during relaxation. In the on-road breathing intervention work by Balters et al. [7], the mean breathing rates under non-driving low workload task, normal driving before the intervention, and stressed driving before the intervention were 12.24, 14.20, and 16.47 breathings per minute, respectively. These values indicate that the driver breathes 16% to 35% faster under a driving task than a low workload non-driving task. We expected that the present GBR setting would prevent the biased on/off operation of the intervention, which came from too high or low GBR value. The detailed procedure of calculating **MBR** is described in section 5.1.1.

While operating the present closed-loop system, the controller laptop distributed the digital intervention signals to the corresponding sensory feedback devices. For the auditory feedback, the Bluetooth speaker (BOSE SoundLink Micro) was connected to the controller laptop wirelessly and emitted the sound from its location behind the headrest of the simulator driver seat. In the digital-to-analog signal conversion of the visual and wind interventions, we utilized the open-source microcontroller, Arduino Uno Rev3, in the middle of the controller laptop and the corresponding sensory feedback devices. Enabling the visual intervention, we placed the 700 mm LED strip (WS2812B) along with the bottom of the 32-inch front screen of the simulator. The installed LED strip consisted of 21 RGB LED pixels and emit the light in maximum power of 6.3 Watt. For activation of the wind intervention, we used the two axial fans (G1238H12B-FSR) attached to each side of the dashboard with an angle of the blowing wind heading to the chest of a driver. We set this orientation of the fans based on an adult driver 6 feet tall. Depending on their height and how upright they sat, drivers experienced the wind anywhere from slightly above to slightly below their chest. The present axial fan had 119 mm diameter and could rotate a maximum of 3200 RPM for a corresponding airflow of 141 CFM. The maximum noise emission from each fan was 46.0 dB(A), which was negligible in its interruption of the auditory intervention signal during its operation under 1600 RPM.



t_0 : the time of the intervention mode switch from the modulation **off** (**CBR<GBR**) to **on** (**CBR≧GBR**)
T : one period of the modulatory intervention signal (=1/**MBR**)

Fig. 3. Time signal of the breathing interventions

4.3 Design of Uni-and Multi-sensory Breathing Interventions

We chose three sensory stimuli of auditory, visual, and wind (tactile + thermoceptive) using a Bluetooth speaker, LED lighting, and two axial fans for breathing intervention. These three intervention modalities were chosen because they do not require any extra devices when considering actual deployment into a real vehicle: they leverage the existing stereo audio, ambient lighting, and ventilation units already present in most cars.

The theoretical background of the present intervention system lies in prior published studies on implicit breathing guides by sensory stimuli during attention-demanding tasks. Auditory breathing interventions using volume modulatory audio have been shown to slow down the breathing rate of a user during demanding computer tasks, and in some cases to also impact their physiological measures such as electrodermal activity, heart rate, and slow cortical potentials measured in EEG [27, 42]. The efficacy of a visual intervention has been shown to influence breathing rates of a computer user viewing subtle change of monitor brightness [27] and a dynamic color gradient in the internet browser's periphery [47]. The subtle modulation of thermal feedback has also been suggested to reduce the breathing rate, but its quantitative effectiveness has not been addressed yet [27]. Also, it has been shown that tactile stimulation can shift the driver's breathing rate from its baseline using a vibrotactile car seat [7, 53]. The effect of combined multi-sensory stimuli on breathing rate control has not yet been addressed in the automotive context and is a new contribution of this work.

We enabled four different options of the uni-and multi-sensory breathing interventions: **INT**$_C$ control intervention, **INT**$_A$ only auditory intervention, **INT**$_{AV}$ auditory and visual intervention, and **INT**$_{AW}$ auditory and wind intervention. The auditory intervention, which showed efficacy in earlier studies [27, 53, 75], was included as a basis for both uni-and multi-sensory breathing interventions to involve manageable sets of intervention combinations. The control intervention was for the control group of the user study. All other interventions were designed for subtle stimulation of the driver's single or multi-sensory system aiming at calming and slowing down their breathing rate without gaining excessive attention. Fig. 3 describes the time signal of each sensory stimulation in four different intervention options.

The control intervention, $\mathbf{INT}_{\mathrm{C}}$, only provided an auditory signal of white noise to a driver with constant volume. We set this constant volume to be at a similar level to the background noise of the car simulator, which emits alike random broadband sound from a running engine and vehicle surroundings through its built-in speaker system. During the auditory intervention, $\mathbf{INT}_{\mathrm{A}}$, the system offered the same type of white noise from the control intervention, $\mathbf{INT}_{\mathrm{C}}$, when **CBR** is lower than **GBR** (modulation OFF condition). However, the volume of the audio signal modulated between 30% and 100% from its baseline at a frequency of the driver's **MBR** when **CBR** is equal or higher than **GBR** (modulation ON condition). During the modulation, the auditory intervention signal smoothly emerges beyond and submerges below the simulator background noise.

The auditory and visual intervention, $\mathbf{INT}_{\mathrm{AV}}$, provided multi-sensory stimulation through the white noise from the speaker and the light emission from the LED strip. The intervention logic and the sound signal of the auditory part followed the same settings of the auditory intervention, $\mathbf{INT}_{\mathrm{A}}$. The brightness of the LED light modulated between 2% and 10% of its maximum capacity at a frequency of **MBR** under the ON condition. During the OFF condition of the intervention, the 2% intensity of the LED lighting was provided to a driver without modulation of the brightness.

Lastly, the auditory and wind intervention, $\mathbf{INT}_{\mathrm{AW}}$, delivered tactile and thermoceptive stimulations to the driver in addition to the auditory feedback. The auditory feedback applied the same operation logic and sound signal of the auditory intervention, $\mathbf{INT}_{\mathrm{A}}$. During the ON condition of the intervention, the two axial fans at each corner of the dashboard blew a wind to a driver with the modulatory fan speed between 400 and 1600 RPM at a frequency of **MBR**. Under the OFF condition, the axial fans rotated at a constant speed of 400 RPM.

5 USER STUDIES

5.1 Procedure

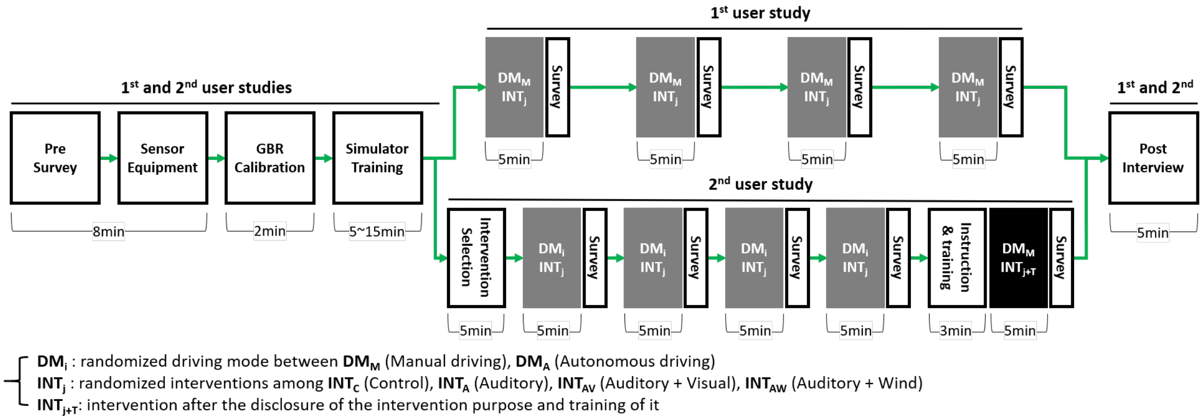


Fig. 4. The overview of the experimental procedure

For testing the hypotheses in section 3, we conducted two stages of user studies using the simulator system with closed-loop single and multi-sensory interventions. As shown in fig. 4, the two user studies applied the same procedures before and after the data collection from the simulator driving. However, each study was designed differently in their selection of the driving modes, the option of choosing the preferred intervention type, and the instruction of using the selected intervention. The first user study aimed to verify the effect of the multi-sensory breathing intervention compared to the unisensory for engaging a driver better to the breathing regulation without disclosure of the operation purpose of the interventions. Thus, it did not demonstrate how to use the ambient feedback to help regulate breathing, nor did it talk about breathing regulation specifically. The stated information in the consent for both studies was "The goal of the study is to use biosensors and video imaging methods to help understand and measure emotions, attention, and engagement in simulated driving conditions."

The second user study was designed to extend the first user study into a more comprehensive analysis of different levels of user involvement in the execution of the intervention and driving task automation, and full demonstrations and explanations were given.

5.1.1 Pre-and Post-procedures of the Simulator Driving. At the beginning of each user study, each participant was requested to read the consent form, after a detailed explanation of the procedure by one of the instructors. The consent form included the overall purpose, procedure, potential risk, and the treatment of the collected data of the study, which were all approved by the Institutional Review Board in advance. However, the instructors did not explain up front the explicit purpose of the intervention devices or how they work to potentially regulate breathing (although participants were free to ask about anything). Once the participant decided on the voluntary participation by signing the consent form, the instructors asked them to fill out the pre-surveys.

The pre-surveys consisted of demographics, the Big-Five Inventory (BFI) [35, 36], and the Patient Health Questionnaire (PHQ-9) [39]. The demographics survey asked the participants about their age, gender, ethnic group, years of driving, frequency of the weekly driving, and the previous experience of the simulator. The collected information from the demographics survey was used for the cohort-based data analysis. The BFI and PHQ-9 surveys provided the necessary information to analyze the influence of the participant's characteristics and the depression level in their interaction with the simulated driving environment.

After the participant filled out the pre-survey, the instructors showed the participant how to put on the Zephyr BioHarness sensor and the Q-sensor, which function and purpose of the use are described in section 4.2. The Zephyr was worn on the chest and the Q-sensor on the right wrist. We chose to measure the EDA on the right hand of the participants to minimize noise related to wrist movement, which was expected to be higher for the left hand used to operate the turn-signal frequently. To enhance the measurement accuracy of the EDA signal, the electrodes of the Q-sensor were extended using the copper wire and attached to the index and middle fingers of the participant.

The participant was guided to take a seat in the simulator for the next step of calibrating the closed-loop breathing intervention system based on their own physiology. Before starting the calibration, the instructor provided the pre-recorded audio guide as follows; *"The system starts to calibrate the in-cabin environment based on your physiological signals for two minutes. Please close your eyes and relax your breathing for 2 minutes with the following white noise."* From the two minutes of the breathing rate collected by the BioHarness sensor, we used the data from the last minute in the calculation of the time-averaged **MBR** value to allow the convergence of the breathing rate for the first minute.

After the calibration, the investigators provided the necessary instruction of driving in the simulated environment, such as the use of steering wheel, gas pedal, brake, gear shift, turn signal lever, horn, and telemetry information on the dashboard. To avoid excessive complexity of the driving task, we chose the automatic gear shift as a basic setup for every participant. Each training session of the simulator consisted of 5 minutes of driving in the designated route of the urban street environment, which is described in section 5.2 with more details. Each participant then repeated the same driving route for the remaining steps of the user studies. For each driving session including the training, many events along the route would be unpredictable (pedestrians, other cars, and bicyclists would appear along the route unpredictably). This was intended to imitate some of the certain and uncertain aspects of a daily commute, with the exception of no traffic jams. Each participant was allowed to rerun the training session until they got used to the simulator driving and memorized the route.

After finishing the main simulator driving segments, described in section 5.1.2, the instructors helped the participant to remove the sensors, and solicited qualitative feedback for 5 minutes.

5.1.2 The Simulator Driving Procedures on the User Study 1.

As shown in fig. 4, the first user study consisted of four driving segments in the manual driving mode, $\mathbf{DM}_{\mathrm{M}}$, with the four different conditions of the interventions: $\mathbf{INT}_{\mathrm{C}}$, $\mathbf{INT}_{\mathrm{A}}$, $\mathbf{INT}_{\mathrm{AV}}$, and $\mathbf{INT}_{\mathrm{AW}}$. The interventions were provided in randomized order. The instructor did not give any information on the intervention type in operation, nor were drivers instructed how to engage with the ambient signals. The goal was to observe drivers' innate responses to the environments.

At the end of each driving segment, the instructor gave a short survey to the participant using a tablet for self-evaluation of their driving experience. The short segment survey included questions about their perception of the interventions, general impression of the driving task, their subjective feeling, and the level of the task load. For asking *"Did you perceive any of the following feedbacks during your driving task?"*, the multiple-choice of the answer was allowed among *"Auditory feedback"*, *"Visual (lighting) feedback"*, *"Aero (wind) feedback"*, and *"None"*. For "general impression", the participant typed their own qualitative description on the tablet. The subjective feeling was evaluated using a 7-point Likert-scale between *"Not at all"* and *"Very much"* for the following questions.

- How pleasantly were you feeling? (Valence)
- How energetic were you feeling? (Arousal)
- How stressed were you feeling? (Stress)
- How would you rate your focus on the driving task? (Focus)

Lastly, the task load in each driving segment was assessed using the Driving Activity Load Index (DALI) [54]. The DALI questionnaire is a revised version of the NASA TLX [31] adopted for the driving task. It is designed to evaluate different components of the workload including the perceptual load, mental workload, and driver's state. The rating scale of the DALI questionnaire is based on a Likert-scale between 0 corresponding to *"Low"* and 5 for *"High*".

5.1.3 The Simulator Driving Procedures on the User Study 2.

As shown in fig. 4, the second user study consisted of both manual driving, $\mathbf{DM}_{\mathrm{M}}$, as well as autonomous driving, $\mathbf{DM}_{\mathrm{A}}$. Before starting to drive a simulator, each participant was asked to select the type of intervention among three choices of $\mathbf{INT}_{\mathrm{A}}$, $\mathbf{INT}_{\mathrm{AV}}$, and $\mathbf{INT}_{\mathrm{AW}}$ based on their preference. To help the choice of the participant, the instructor provided the following audio record and operation of each mode; *"In the present driving segment, you can select one from three different in-car interventions, which are designed to calm your breathing while driving. Please experience each of the interventions and select the most pleasant one that provides a minimal distraction. First, auditory intervention [auditory intervention example]. Second, auditory and visual intervention [auditory and visual intervention example]. Third, auditory and wind intervention [auditory and wind intervention example]."*

After the selection of the intervention, the instructor asked the reason for their selection. Upon a selection of the intervention, instructors randomized the first four driving segments with different conditions of driving mode, $\mathbf{DM}_{\mathrm{i}}$, and intervention, $\mathbf{INT}_{\mathrm{j}}$; $\mathbf{DM}_{\mathrm{M}}$ and $\mathbf{INT}_{\mathrm{C}}$ manual driving mode and control intervention, $\mathbf{DM}_{\mathrm{M}}$ and $\mathbf{INT}_{\mathrm{S}}$ manual driving mode and the selected intervention, $\mathbf{DM}_{\mathrm{A}}$ and $\mathbf{INT}_{\mathrm{C}}$ autonomous driving mode and control intervention, and $\mathbf{DM}_{\mathrm{A}}$ and $\mathbf{INT}_{\mathrm{S}}$ autonomous driving mode and the selected intervention. When it came to the first autonomous driving mode, the pre-recorded audio script introducing the autonomous mode was provided to the participant as follows; *"The system is now switching to autonomous driving mode. Please take your hands off the steering wheel."* The breathing regulation purpose of the selected intervention signal was not provided to the participant during the first four driving segments for the similar reason of the first user study, which was intended to observe their innate perception and response to the given environment. The instructor only informed the combination of the driving mode (manual or autonomous) and the intervention (the control or the selected intervention) to the participant.

The last driving segment consisted of the manual driving mode, $\mathbf{DM}_\mathrm{M}$ and the selected intervention, $\mathbf{INT}_\mathrm{S}$. Before starting the session, the instructor provided the instruction and training to the participant about how to engage with the chosen type of intervention in the regulation of their breathing pattern. At this time, the pre-recorded audio guide was also given with the sample operation of the selected intervention as follows; *"In the present driving segment, we will explain in more detail your selection of the intervention and provide you a short training of it. Your chosen in-car intervention is invented to calm your breathing rate through the subtle change of [auditory signal / auditory signal and brightness of LED lighting around the driving scene / auditory signal and aero-feedback from the two axial fans installed at each side of the dashboard]. To guide your breathing rate, the intensity of each signal modulates between 30 and 100 percent of its maximum [volume / capacity], which decreases during the inhalation period, and increases during the exhalation period. Please follow the intervention signal for three breathing cycles. [three cycles of the selected intervention operation] Great job. The in-car interventions are not always on. When it is on, you can try to regulate your breathing rate by following the signals. The provided breathing rate of the interventions can be different from this example, depending on the context of the study. In any case, however, safety driving is the most important task rather than following the intervention. Hope you enjoy the next driving segment."*

Once the participant got to know how to interact with the intervention, it was not possible to make them unaware of the breathing regulation purpose of the signal. For this reason, we put this driving segment at the end instead of randomizing its order with the first four driving segments. To alleviate the fatigue of the participant over the four-driving segment, the instructor allowed the participant to take a 5 minute break. Also, it is expected that participants would start to drive better with more practice; to mitigate that effect on their performance, we allowed participants during the up-front-training to take as many sessions as they wanted to feel comfortable maintaining a consistent driving performance for the rest of the study.

At each end of the driving segment, a short survey was provided to the participant. The list of the questions was the same as for the first user study, except we omitted asking about the (other, non-selected) intervention types.

5.2 Driving Route and Environment

We chose the simulator's urban driving scenario for both user studies. The urban driving is supposed to be more stressful compared to the others, such as highway driving [32], and thereby provides a challenging test to deploy a breathing intervention. As shown in fig. 5, the present study used the designated driving route rather than randomizing to minimize the physiology and subjective rating change coming from the different driving paths. The repetition of the driving route was also expected to play a role in imitating the daily commuting experience, which is known to be one of the most common driving patterns [48] with a negative impact on physiological health and quality of living [52]. The designated driving route consisted of 160 meters of the road to the first roundabout entry and 1100 meters of the round trip along with the medium urban traffic condition. The route was designed to be easy to remember to avoid any added cognitive load that may alter the driving performance. Each participant was able to finish the round trip route by taking the first exit on the right at every roundabout, and the right turn at every intersection. By selection of the medium traffic condition, the simulator randomized the spontaneous behavior of the surrounding vehicles, pedestrians, and bikers with maintaining a medium level of complexity and the corresponding driving task load.

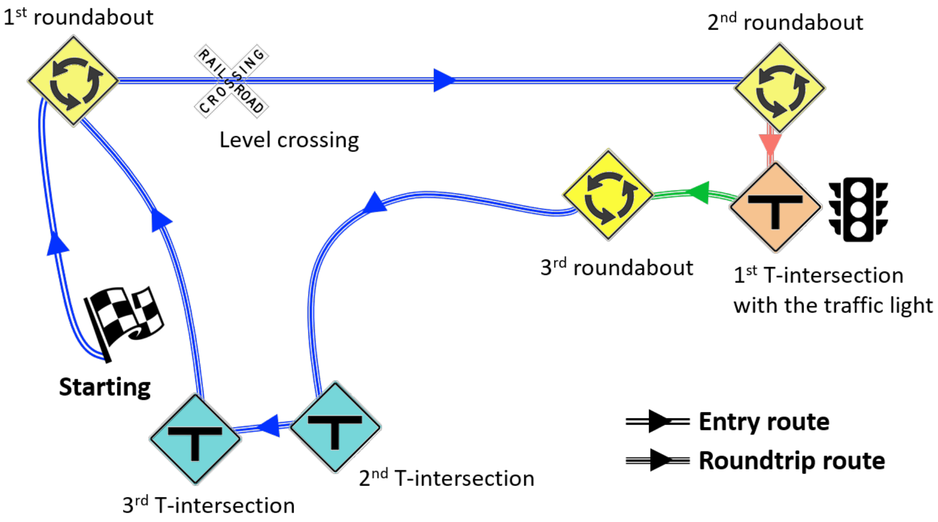


Fig. 5. The designated urban driving route for every user study segment

5.3 Data Description: Participants and Collected Data

A total of 26 participated in the first study, and 36 in the second study. Eight of these participants overlapped, participating in both studies, and we will analyze them below both within their cohorts and separately. Table 1 describes the cohorts. For the first study, the data of three participants had to be excluded from analysis due to missing EDA signals. For the second study, the first three trials were considered as pilot tests, allowing us to adjust the system, and one participant's dataset was discarded due to motion sickness and inability to finish the study; this resulted in 32 participant datasets from Study 2 for further processing. Of these, one had missing EDA in Study 2. Thus, we have 31 datasets for Study 2, with eight participants overlapping with Study 1. Both studies involved a balanced cohort in terms of gender, almost equal age ranges, and the number of novice participants to the simulated driving (see Table 1 for more details). In terms of the depression severity, extracted from the responses provided by the participants, to the PHQ-9 questionnaire, the cohort of the first study included 8 depressed, 8 mild, and 7 not depressed. We used the PHQ-9 score, which corresponds to the sum of the scores provided by the participants to the 9 first items of the questionnaire, to determine the depression severity. We consider a cut-off of 10 to consider the driver as depressed [43]. The driver is considered as not depressed if his/her PHQ-9 is less than 5, and mildly depressed if between 5 and 9. For the second study, 8 were depressed, 10 mild and 13 were not depressed.

For both studies, we collected data related to the driving performance, the driver's physiology, and the responses to the questionnaires listed in Section 5.1.2. In terms of driving performance, the total number of crashes and infractions is considered for analysis. The infractions are the errors related to the regulation of trajectory (e.g., speed, lane tracking) and basic maneuvers (e.g., lane changes, execution of turns, obedience to traffic signs and signals). We noticed that only four types of infractions varied for all the participants, namely: lane tracking, non-use of turn signals, speed exceeded, and speed less than 50% of the allowed. We considered the normalization of the infractions using the min-max range normalization to remove the component related to the driving style of each participant and to be able then to compare within-subjects.

Table 1. Description of the cohort for the user study 1 and user study 2

	User study 1	User study 2
Total number	26	36
Complete datasets	23	31
Gender	12 female	16 female
Age (years)	Mean=30.71 (SD=7.95)	Mean=31.86 (SD=9.92)
Driving experience (years)	Mean=9.79 (SD=8.10)	Mean=12.5 (SD=10.81)
Previous experience with simulator	61% novice	58% novice

In terms of the physiological signals, we measured the breathing rate (BR) and the Electrodermal Activity (EDA). For each 5-minute segment of driving, we computed the average breathing rate. We obtained the Normalized Breathing Rate (NBR), which reflects the "engagement level" in the breathing guide, by dividing this 5-min-average BR by the participant's goal breathing rate. Each person's goal BR was obtained after their calibration session. For EDA, we first applied an exponential smoothing to reduce the noise and then normalized the signal by the min-max ranges computed over the whole recorded signal. We decomposed the normalized EDA into phasic and tonic components, which is a standard way of processing EDA as both the tonic and phasic levels can increase separately with increasing arousal [11, 15]. For each 5-minute segment of driving, we considered the average of the tonic level of the EDA and the total number of significant peaks extracted from the phasic components. We asked the participants to rate their latest experience after each segment in terms of the attention, visual, auditory, and temporal demand, as well as the interference and the situational stress, on a Likert scale varying from 0 (low) to 5 (high). The workload score was computed using these dimensions by summing the obtained ratings and normalizing by 30.

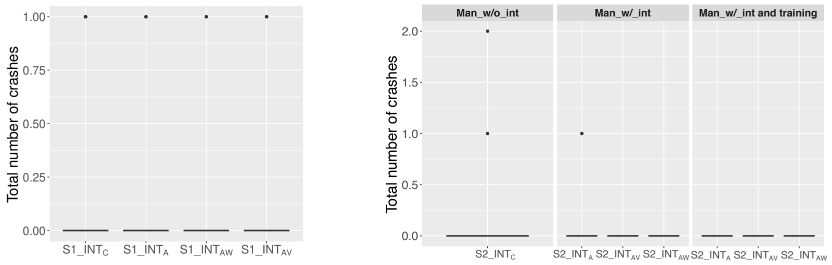
6 FINDINGS

This section describes the quantitative and qualitative results from the two user studies. We present evidence of cases where the simulated driving mimics real-world driving, and we perform data analysis to evaluate the efficacy of the designed intervention and to test the five hypotheses presented in Section 3. The efficacy of an automotive HMI can be measured in terms of usability or how easy the interface is used, distraction, or driving safety and acceptance [25]. For this study, we consider the sensory feedback reflecting the breathing intervention as the automotive HMI. The efficacy is measured in three areas: user engagement in the breathing intervention, driving safety, and user acceptance. To detect the statistical difference in the collected data across three or more conditions, we used the Friedman test for the paired samples and the Kruskal-Wallis for the non paired comparison. The pairwise comparison was performed using the Wilcoxon test with the Bonferroni correction, considering a significance threshold of 5%.

6.1 Mimicry of Real-world Driving

Car simulators offer a naturalistic setting close to the real-world driving environment nowadays through advanced features. However, experienced drivers who are novices in the simulator can still have a lot of accidents in the simulator. The car simulator used in our study offers a realistic setting with its features described in Section 4.1. However, after conducting pilot tests, we noticed that drivers who were new to simulated driving had a higher number of crashes than those who had prior simulator experience. To reduce the effect of the car simulator novelty, we offered all drivers the chance to repeat the training session as much as they want, so they become familiar with driving in the car simulator and minimize the number of crashes. For the participants who had one or more accidents during the simulator training session, we asked them to repeat another training session. For example, for the second study, 6 participants repeated the training session twice by driving the same designated route for 5 minutes each segment. Three of them were involved in one or two accidents during the training sessions. We also had one participant who found it difficult driving the car simulator and repeated the simulator training session four times before feeling habituated to its driving.

The in-car intervention, if not subtle enough, may alter the driving performance resulting in safety issues [75]. To check the intervention subtlety, we compared the distribution of the total number of crashes for each type of intervention to the control condition. Fig. 6 shows the boxplots of crash counts for both Study 1 and Study 2 per condition. We compared the total number of crashes to zero for each condition type for both studies using a one-way Wilcoxon test. For the first study, the difference was not significant for all the conditions: Control (**INT**$_{\mathrm{C}}$), auditory (**INT**$_{\mathrm{A}}$), auditory and wind (**INT**$_{\mathrm{AW}}$), and auditory and visual (**INT**$_{\mathrm{AV}}$). For the second study, there was no significant difference when comparing the total number of crashes to zero per conditions, namely: without intervention, with intervention, and with intervention and training. Fig. 6b depicts the boxplots of the total number crashes corresponding to the different conditions across the different selected types of interventions: auditory, auditory+visual, and auditory+wind. For the control condition (intervention OFF), one of the participants went out of the designed route during the control condition, which caused confusion and induced 3 collisions. Except for one of the remaining participants who had a crash, no one else was involved in a collision. When the intervention was ON without training, only two participants had 1 crash. No participant was involved in a collision for the intervention ON with training condition.

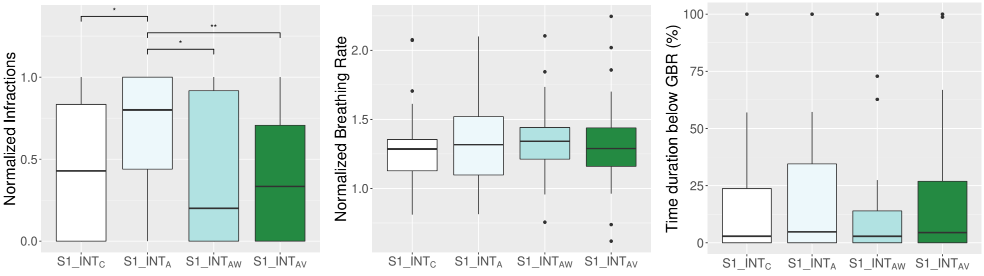


(a) (b)

Fig. 6. Boxplots of the total number of crashes for the (a) Study 1: corresponding to control condition (denoted hence **S1_INT**$_{\mathrm{C}}$), the auditory intervention (denoted **S1_INT**$_{\mathrm{A}}$), for the auditory and visual (denoted **S1_INT**$_{\mathrm{AV}}$), and for the auditory and wind (denoted **S1_INT**$_{\mathrm{AW}}$), and (b) Study 2: corresponding to the manual driving without intervention .

For both studies, the total number of crashes is almost null, which suggests that the simulated driving without and with intervention is close to the real-world driving in terms of accidents.

Among the non-crash infractions, we consider driving above the speed limit and "out of track" violations as more serious offenses compared to non-use of turn signals and speed less than 50% of the allowed limit. In fact, speeding and "out of lane" driving are among the most frequent driving behaviors reported for drivers and motorcycle operators involved in fatal crashes, provided by the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA 2018). Speeding is the first driving behavior while "out of track": failure to keep in the proper lane was the third most frequent driving behavior. We examined the infractions involved in the crashes for both Study 1 and 2. Two crashes were caused by speeding (15% of the total collisions), 8 crashes (61%) happened due to being "out of track", and the remaining three collisions were related to driver distraction. When examining the external scene videos, we noticed that 5 (31%) of the collisions happened due to



(a) (b) (c)

Fig. 7. Boxplots of the (a) normalized total number of infractions and (b) normalized breathing rate (c) the percentage of time duration below goal breathing rate corresponding to the control condition: intervention OFF (**INT**$_\mathrm{C}$), auditory (**INT**$_\mathrm{A}$), auditory and wind (**INT**$_\mathrm{AW}$), and auditory and visual feedback (**INT**$_\mathrm{AV}$). Note that **: $p \leq 0.01$ and *: $p \leq 0.05$.

failure to stay on the track, while the remaining 3 (23%) were caused after failing to yield on right of way. The failure to yield right of way is also counted among the four most serious driving behaviors that lead to fatal crashes in the US. This section confirms part of Hypothesis H1 by verifying that the breathing guide intervention reflected by the sensory stimulation did not alter driving safety.

6.2 Efficacy of the Multi-sensory Compared to the Unisensory Feedback

To judge the efficacy of the breathing intervention, we recall that three aspects are considered: driving safety, user engagement in the intervention, and user acceptance. We used the number of infractions to evaluate driving safety. Since the two user studies are designed to test the efficiency of the breathing intervention, we use the features extracted from the breathing rate to evaluate the driver's engagement in the intervention as well as the subjectively reported workload and focus level. Based on the work of Kulviwat et al. [40], the affect arousal and pleasure have an effect on attitude toward technology adoption. Therefore, we use the reported pleasure and energy (reflecting the reported arousal) to assess the intervention's acceptance by the participants. We consider the EDA data to evaluate the arousal level experienced during each condition objectively, as it has been repeatedly demonstrated to reflect physiological arousal levels [15]. The stress caused by the inability to engage with a new technology, usually known as technostress, decreases users' satisfaction, and subsequently their technology acceptance [65]. We consider the reported stress when studying the user's acceptance of the breathing intervention.

We designed the first user study to reveal if the multi-sensory feedback enhanced the unconscious engagement to the intervention, compared to the unisensory feedback, while maintaining or improving the driving performances of the participants and user acceptance of the intervention. The unisensory feedback is presented by the **INT**$_\mathrm{A}$ and the multi-sensory concerns both the **INT**$_\mathrm{AW}$ and **INT**$_\mathrm{AV}$ feedback. We considered the normalized total number of infractions to evaluate the driving performances. The normalized total number of infractions was significantly different across the conditions (Friedman chi-squared = 10.57, df = 3, p = 0.01). Fig. 7a shows that the boxplot corresponding to the **INT**$_\mathrm{A}$ is higher than the infractions corresponding to **INT**$_\mathrm{AV}$, **INT**$_\mathrm{AW}$ and **INT**$_\mathrm{C}$. This shows that participants committed more infractions when exposed to the unisensory intervention compared to the intervention OFF and to the multi-sensory feedback. There was not a significant difference for the normalized infractions between the Control condition and the multi-sensory interventions.

Second, we considered the Normalized Breathing Rate (NBR), the percentage of time duration below Goal Breathing Rate (GBR), the reported workload (assessed using the DALI questionnaire), and focus on evaluating the user engagement in the breathing intervention between the different tested feedback. We recall that the NBR is obtained by dividing the average BR, captured during each 5-minute driving segment, by the participant's goal breathing rate, obtained after the personalized calibration session. The percentage of time duration below GBR represents the time duration of a participant breathing under GBR divided by the total duration of time in each driving segment. Fig. 7b and 7c shows the boxplots corresponding to the normalized BR and the time duration below GBR, respectively, for the four segments. There was no significant difference in the NBR (Friedman chi-squared = 5.03, df = 3, p = 0.17), the percentage of time duration below GBR (chi-squared = 2.01, df = 3, p = 0.57), the reported focus (chi-squared = 3.62, df = 3, p = 0.31), and the reported overall workload (chi-squared = 5.91, df = 3, p = 0.12) when using the Friedman test to compare between the control condition, unisensory and multi-sensory feedback. These findings show that the multi-sensory interventions tested in this study have the same level of engagement as the unisensory auditory one and the control condition when the breathing guide is turned off. We should mention that the NBR values collected during the different conditions are far from 1, which corresponds to 100% of engagement to the GBR. We recall that the interventions turn on the breathing guide when a driver breathes faster than GBR. Accordingly, the low percentage of time under GBR in Fig. 7c represents that the interventions were mostly active throughout the corresponding driving sessions but could not engage the participants to the breathing guide signal.

Finally, we investigated the user acceptance of the multi-sensory interventions compared to the unisensory intervention and to the control condition. For this, we considered the reported pleasure, energy, and stress ratings. The difference between the four conditions is not significant for the pleasure ratings (Friedman chi-squared = 4.38, df = 3, p = 0.22), the energy (chi-squared = 5.68, df = 3, p = 0.13) and the stress (chi-squared = 1.54, df = 3, p = 0.67). After each driving segment (hence feedback), the participants were asked to rate how much they felt energetic while driving. This metric reflects the subjective affect arousal. To verify if the results obtained from the analysis of the subjective arousal are consistent with the objective measure of the arousal (reflected by the EDA), we considered two EDA features, namely: the total number of peaks and the average of the tonic level over each driving segment. The EDA signal is usually characterized by a sequence of overlapping phasic responses (peaks) overlying a tonic component. Phasic responses are usually associated with short-term events/stimuli while the tonic component generally reflects the level of EDA when no particular environmental events occur. We consider the total number of peaks per driving segment to assess the short-term events that affected the driver. The average of the tonic level is considered to evaluate the baseline arousal during the driving segments. These two features have been used by different studies in the automotive field [32, 53, 75]. There is no significant difference in the features extracted from the EDA across the four conditions. This supports the conclusion that the participants had the same level of overall arousal during the driving tasks for the multi-sensory feedback compared to the unisensory feedback.

This section first treated Hypothesis H0 by comparing both unisensory and multi-sensory interventions to the control condition. It also investigated Hypothesis H2 by checking the user engagement in the multi-sensory compared to the unisensory. The results show that there is no significant reduction of the drivers' BR when exposed to the breathing guide compared to the control intervention. The driving performance was altered in terms of infractions for the auditory (unisensory) intervention, while the multi-sensory feedback did not alter the driving performance compared to the control intervention. The user acceptance level remains the same compared to the control intervention. To sum up, the sensory feedback (uni- and multi-) did not help the drivers subconsciously reduce their breathing rate. In addition, there was no significant difference in the efficacy of the unisensory compared to the multi-sensory feedback. Thus, Hypotheses H0 and H2 were not confirmed.

Note: For sections 6.3, 6.4, and 6.5, we use $\boldsymbol{INT}_C$ *to designate the driving segment corresponding to the control intervention (white noise) and* $\boldsymbol{INT}_{BG}$*, BG stands for "Breathing Guide" for all the different types of feedback selected by the participants among auditory (*$\boldsymbol{INT}_A$*), auditory+visual (*$\boldsymbol{INT}_{AV}$*), and auditory+wind (*$\boldsymbol{INT}_{AW}$*).* $\boldsymbol{INT}_{BG+Training}$ *corresponds to the driving segment with the breathing guide after completing the intervention training session.*

6.3 Efficacy of In-car Interventions with Drivers Actions

This section investigates the effect of asking the users for two types of actions related to the efficacy of the in-car interventions. The first action was when they selected one of the three types of ambient feedback, and the second action was how well they matched their breathing rate to it after they were provided with a training session (Study 2, final drive only).

6.3.1 Effect of Users Choice Selection. First, we wanted to verify if allowing the driver to select the preferred type of the sensory feedback increases the chance of his/her engagement and acceptance of the breathing intervention. In user study 2, we gave the user a choice after the simulator training session to select the least distracting intervention between the auditory, auditory and wind, and auditory combined to the visual, using the script detailed in Section 5.1.3. For the 31 participants, the auditory with the wind was selected by 16 participants (51.6%), followed by the auditory intervention which was selected by 12 drivers (38.7%), while the auditory with the visual intervention was selected by only 9.7% of the participants. The participants reported that the auditory feedback was natural and subtle; some of them chose to select the wind with it to be able to perceive the intervention. Others found that the wind was having a refreshing and soothing effect. All the users (except 3 of them) reported that the light seemed to be the most distracting when driving, so they did not select it. Table 2 presents the distribution of the selected intervention per gender, driving experience, previous experience driving a car simulator, and depression level. For instance, for the participants who selected the auditory intervention, 50% of the participants were women, 66.7% had a driving experience more than five years, 33.3% tried a car simulator before, and 41.7% were not depressed. We note that even though we report the data related to the auditory with the visual intervention in the last column of Table 2, we do not statistically compare it with the other types of feedback because only three participants selected $\mathbf{INT}_{\mathrm{AV}}$. We notice that the percentage of the participants who were novices at simulator driving is higher (66.7%) for the unisensory intervention than the multi-sensory wind intervention (50%). This suggests that novelty to the car simulator may have affected the choice of the intervention.

Table 2. Distribution of the selected intervention per gender, driving experience, previous experience driving using a car simulator and depression level.

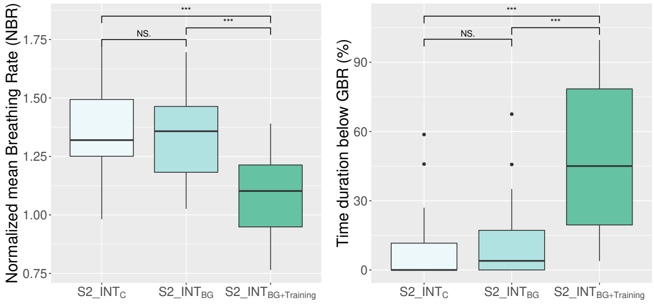
		$\mathbf{INT}_{\mathrm{A}}$	$\mathbf{INT}_{\mathrm{AW}}$	$\mathbf{INT}_{\mathrm{AV}}$
Gender	F	50.0%	37.5%	66.7%
	M	50.0%	62.5%	33.3%
Driving experience	5+	66.7%	75.0%	66.7%
	5-	33.3%	25.0%	33.3%
Tried simulator	Yes	33.3%	50.0%	33.3%
	No	66.7%	50.0%	66.7%
Depression	None	41.7%	37.5%	66.7%
	Mild	25.0%	37.5%	33.3%
	Depressed	33.3%	25%	0%
Total number of participants		**12**	**16**	**3**

In terms of engagement, there was no significant difference between the with and without intervention, for the NBR (Wilcoxon paired test p=0.12), the percentage of time duration below GBR (Wilcoxon paired test p=0.11), reported workload (Wilcoxon paired test p=0.24), and focus (Wilcoxon paired test p=0.07).

In terms of the user acceptance of the feedback, there was no significant difference between the self-reports after conditions with and without intervention, for the reported pleasure (Wilcoxon paired test p=0.07), energy (Wilcoxon paired test p=0.24), and stress (Wilcoxon paired test p=0.19). No significant difference was found in the EDA features: the mean tonic level (Wilcoxon paired test p=0.40) and the total number of peaks (p=0.48).

In this subsection, we examined Hypothesis H3, and we verified that giving the choice of selection of the preferred feedback to our participants did not improve their engagement significantly to the feedback. However, their acceptance level remained the same as in the condition without feedback. When comparing the overall reported pleasure, energy, and stress between the two studies, we found that the participants rated the pleasure level significantly higher for the second study compared to the first one (Wilcoxon p<0.001). One might expect a higher stress level for the first study compared to the second one due to the fact that the participants did not have any information about the intervention type which could induce uncertainty about experiments and thus increase the stress level. However, no significant difference was detected for the stress level (Wilcoxon p=0.08). The difference was not significant for the reported energy level (Wilcoxon p=0.55). These results indicate that pleasure increased when the participants got to choose what they wanted to experience as stimulation.

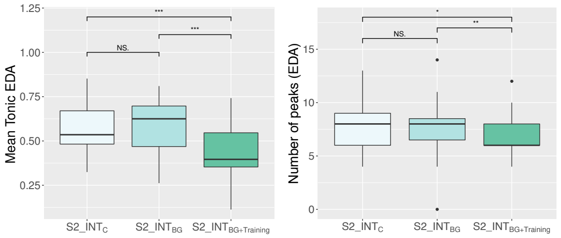
6.3.2 Effect of the Intervention Training. We investigated the effect of the intervention training on the user engagement and acceptance. Before the last segment of driving, we explained the intervention and trained participants in how to engage with it, using the script listed in Section 5.1.3.



(a) (b)

Fig. 8. Boxplots of (a) the normalized mean breathing rate (b) the percentage of time duration below GBR corresponding to the manual driving segment when the intervention is set to the Control condition ($\mathbf{INT}_\mathrm{C}$), when the breathing guide is ON without training ($\mathbf{INT}_\mathrm{BG}$), and the driving segment after the intervention training session ($\mathbf{INT}_\mathrm{BG+Training}$). Note that ***: $p \leq 0.001$.

We asked the participants to focus on the driving task as the main task and to feel free to try to match the modulation of the sensory signals with their breathing rhythm, whenever they felt able to do it without altering their driving performance. Fig. 8 shows that the values of the normalized breathing rate and the percentage of time duration below GBR corresponding to the manual driving segment during the control condition are not different compared to those corresponding to the manual driving when the Breathing Guide was suggested. However, the boxplot corresponding to the NBR values after the intervention training session is lower than the control and $\mathbf{INT}_\mathrm{BG}$ conditions. This was validated by the statistical test performed using the Wilcoxon paired test (both p<0.001). With the given training session, the participants breathed under goal breathing rates significantly longer over the driving session compared to the control and $\mathbf{INT}_\mathrm{BG}$ conditions, which are proved by the corresponding Wilcoxon paired tests (both p<0.001). This suggests that priming the participants using a training session is important for this breathing guide to be efficient. There was no significant difference between the conditions with and without training for the reported workload (p=0.28) and focus (p=0.92).



(a) (b)

Fig. 9. Boxplots of the (a) mean tonic EDA and (b) total number of peaks corresponding to the driving segment when the intervention is ON without training (**INT**$_{\text{ON}}$) and the driving segment after the training session (**INT**$_{\text{ON+Training}}$). Note that ***: $p \leq 0.001$.

In terms of the user acceptance, no significant difference was observed between the two conditions for the reported pleasure, energy, and stress. However, the EDA was significantly different between the two conditions (Fig. 9). Note that an extra detrending step was applied to the tonic level of the EDA to remove any potential effect related to the fact that the session **INT**$_{\text{BG+Training}}$ was the last driving segment. In fact, the mean tonic EDA and the total number of peaks were both significantly lower for the session after training than the one without training (Wilcoxon paired test p<0.001 and p=0.008 respectively). Asking the participants to match their breathing rhythm with the modulation in the sensory feedback was expected to raise the drivers' workload, and thus their arousal level. Based on the data, the affect arousal was significantly lower during the driving segment after the training session. This might be explained by the fact that the training session helped the participants by reducing the uncertainty and stress typical of situations having no instructions and having "unexplained stimuli".

To summarize, the intervention training provided to the participants allowed to improve the engagement significantly in terms of the breathing rate and did not change the reported focus and the cognitive load levels significantly. This confirms hypothesis H5. In fact, a significant increase in the workload and the focus levels were supposed to be perceived by the participants. However, the difference in the subjective metrics corresponding to the driving segment before and after the training session was not significant. This finding suggests that, with training, the participants could easily balance their perception of the breathing intervention and maintain the quality of their driving.

Some of the drivers (n=8) who participated in the second study participated in the first study as well. Five of them selected the auditory and wind intervention, 2 selected the auditory, and only one chose the auditory combined with the visual feedback. We examined the engagement to the intervention between the two studies among these participants in terms of the normalized breathing rate (NBR). Fig. 10 shows the boxplots of the NBR corresponding to each type of intervention crossed with the study reference. The boxplots corresponding to the intervention **INT**$_{\text{C}}$ contain all 8 participants' NBR values. The values show a trend to be higher during the second study compared to the first one. We recall that only 2 participants selected the auditory intervention. For this type of intervention, the values of the NBR are higher during the second study without training compared to the first study. For the 5 participants who selected the auditory and wind feedback, the values of the NBR for Study 2 tend to be lower compared to Study 1. The same conclusion applies to the participant who selected the **INT**$_{\text{AW}}$. For all the different types of feedback, the training helped the participant improve their engagement in the intervention (NBR lower than without training). While we can not conclude due to the low sample size, it seems that repeating the experiment with the choice of selecting the preferred feedback helped increase the engagement, particularly for the multi-sensory interventions. This aspect needs more investigation in the future.

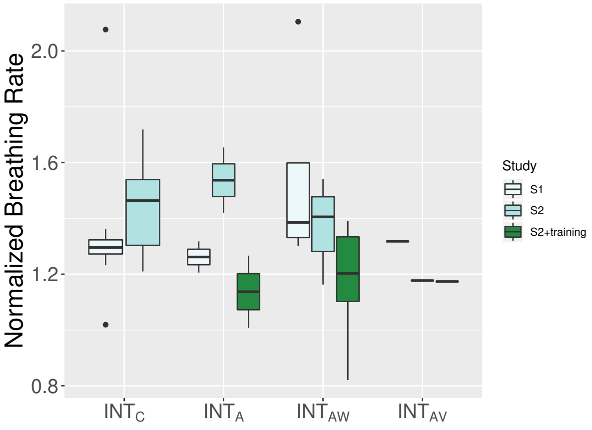


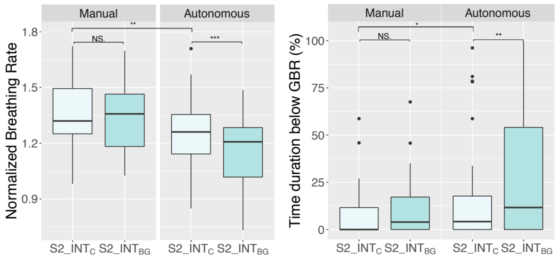
Fig. 10. Boxplots of the normalized Breathing Rate between Studies 1 and 2, for the different types of interventions for the eight drivers who participated in both studies.

6.4 Effect of Automation of the Driving Task

The extension installed to the car simulator allowed us to create and test an "autonomous" mode by having an experienced and trained driver controlling the car simulator remotely. Four participants reported feeling motion sickness, which was relieved for one of them with the wind sensory feedback.

Before investigating the effect of the driving task automation on the user's engagement to the Breathing Guide, we calculated the sole influence of the automated driving within control conditions of manual and autonomous driving modes. Fig. 11a and 11b are the boxplots corresponding to the NBR and the time duration below GBR, respectively, for two different driving modes with and without the Breathing Guide. We found that the NBR values corresponding to the autonomous mode were significantly lower than the manual mode in control conditions (Wilcoxon paired test p <0.01). The percentage of time duration below GBR was higher under the control condition in autonomous driving than in manual driving (Wilcoxon paired test p=0.04). The differences also hold for all the lower reported workload, focus, energy, and stress (all the Wilcoxon paired test p<0.001). The same result was confirmed for the EDA features: both the lower mean tonic level and the total number of peaks (both Wilcoxon paired test p<0.001). There was no significant difference in the reported pleasure (Wilcoxon paired p=0.13). These results imply the noticeable impact of autonomous driving itself on reduced driver's breathing rate, reduced workload, and lower subjective stress feelings reported, while maintaining equal levels of reported pleasure.

We compared also each participant's response between autonomous driving with and without the Breathing Guide. As shown in Fig 11a, the NBR value corresponding to the Breathing Guide was significantly lower than the value of the control condition (Wilcoxon paired test $p < 0.001$). In Fig. 11b, the percentage of the time duration below GBR was significantly higher under the Breathing Guide than the value of the control condition (Wilcoxon paired test p = 0.011). There were no significant differences in other parameters. This impact of the Breathing Guide under autonomous driving differs from the corresponding outcomes from manual driving, which did not show the significant difference in the breathing rate between the Breathing Guide and the control condition.



(a) (b)

Fig. 11. Boxplots of (a) normalized breathing rate (b) the percentage of time duration below goal breathing rate corresponding to the manual driving with control condition (**DM$_M$_INT$_C$**), the manual driving with the Breathing Guide (**DM$_M$_INT$_{BG}$**), the autonomous driving with control condition (**DM$_A$_INT$_C$**), and the autonomous driving with the Breathing Guide (**DM$_A$_INT$_{BG}$**) Note that *: $p \leq 0.05$, **: $p \leq 0.01$ and ***: $p \leq 0.001$

These results suggest that the subconscious engagement in the intervention, in terms of the breathing rate, is different when we remove the driving task while it is the same when performing the driving task.

To further investigate this finding, we considered the NBR per zone as described in Fig. 5. In fact, we considered six zones where the driving task difficulty is supposed to be different: straight routes, roundabouts, intersections, before the traffic light, at the (red) traffic light, and after the traffic light turns green and they drive ahead. The intersection and roundabout zones include the areas 10 meters ahead and 10 meters after these places. The zone before the traffic light includes the area 10 meters after the second roundabout and before at the traffic light zone. The traffic light zone is the spot where the car stops at the 1st T-intersection with the traffic light. The zone after the traffic light includes the area after the traffic light zone and 10 meters ahead of the 3rd roundabout. The rest of the area was designated as a straight road. We considered the detailed segmentation around the traffic light to be able to check if waiting at a red light influences the engagement level. For each driving segment, we separately calculated the breathing rate during the car running in each zone. The average time duration of a simulated driving in each zone is shown in Fig. 12.

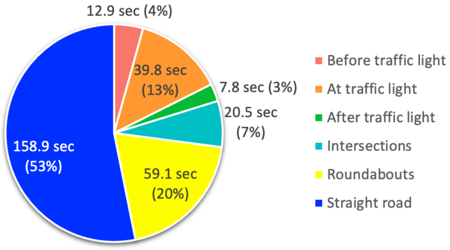


Fig. 12. Averaged time duration at each road zone.

Fig. 13 depicts the boxplots of the NBR by condition per road zone type. It shows that for the manual driving during the Control (**INT$_C$**) and Breathing Guide (**INT$_{BG}$**) conditions, the distributions are almost at the same level, higher than 1, except for the values corresponding to the NBR "after the traffic light" zone, which tends to be lower when the intervention is ON. However, after running the Kruskal-Wallis test to check the difference, we found that the values were not significantly lower than the other zones. For the autonomous mode, the intervention appears to lower the NBR, reflecting a higher engagement from the participants. We see the road zone type does not influence the NBR (this was confirmed also with the statistical test). For the manual mode with the breathing guide turned on and after training ($\mathbf{INT}_{\text{BG+Training}}$), the boxplots corresponding to the intersection, roundabouts, and straight routes were higher than the other road zones around the traffic light. A significant difference was found for the $\mathbf{INT}_{\text{BG+Training}}$ (Kruskal-Wallis chi-squared = 13.37, df = 5, p-value = 0.02). When performing a multiple pairwise comparison using the Dunn's Bonferroni adjustment, the only significant difference that was detected corresponds to the driving segment after the traffic light turns green and the participants drove ahead, which is lower than the straight route (p=0.008). We note that the 30-second window for the breathing rate calculation could cause some moments of slower breathing from waiting at the traffic light to contribute to the lower rate during the time "after" the light.

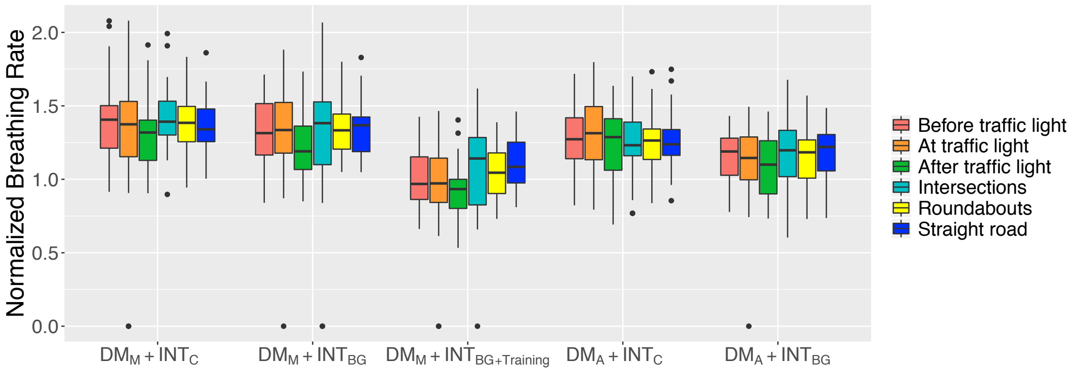


Fig. 13. Boxplots of the normalized Breathing Rate corresponding to the different conditions per road zone.

6.5 Qualitative User Feedback

In this section, we review the open remarks provided by the participants in terms of perception and preferences related to the intervention, feedback on the protocol and intervention design, and some suggestions.

6.5.1 Perception of the Intervention. In terms of the sensory feedback, all the participants found that the auditory stimulation was subtle and natural. Some of them felt that it was too subtle and chose to have the wind in order not to get drowsy. Two participants said that they felt drowsy after experiencing the auditory intervention and attributed that to the fact that they listen to white noise to help them fall asleep at night. The light was considered distracting by all the participants except two out of the three who selected it as the preferred feedback. In fact, the third one selected it while he liked the wind more because he was wearing contact lenses, and he said that the wind, facing his eyes, would dry them. One of the participants who selected the light and the auditory stimulation was a novice driver and reported that he focused on the driving task and could not perceive the modulation in the LED lights signal. The wind was described as "refreshing" and "increased the drivers' focus" for the participants. In fact, one participant experienced an accident in his route and felt stressed, but told us that the wind reminded him to focus on breathing more calmly, which reduced his stress level. Four users reported that the intervention was subtle and that it was easy to alternate their attention between it and the driving task. One said that it was easier to follow the intervention signal while waiting for the red light to turn green.

In terms of the user's involvement indicated by the choice selection and their response to the training, some participants liked the fact that they were asked to select the preferred sensory stimulation. They reported that this is expected to improve their well-being and engagement in the intervention while driving. After the training with the intervention and asking the participants to engage with it (if possible), three participants, one of them a novice driver, found that engaging with the intervention was so distracting that they simply ignored it. One of them preferred to have it during the autonomous mode. The way to engage with the breathing intervention during the first four segments, before the explanation, was described as "so natural" (2 participants reported this) and "straightforward" for a participant who practiced yogic breathing. In terms of the breathing rhythm matching with the modulation, one driver reported that she expected the opposite engagement phase of inhalation and exhalation to the intervention signal. Before the last segment, the participant thought and felt that the rate of the intervention followed her breathing rate.

Three participants reported that they like to be in control when they are driving and they hate being driven, so they did not like the autonomous mode. One said that she could not trust the car and the AI to take control. (Note that we did not say an AI was driving). The intervention was perceived differently during the autonomous drive, compared to the manual mode.

6.5.2 Protocol and Intervention Design. We received some comments about the protocol design. Two participants wanted to select different types of feedback during the autonomous mode. In fact, they wanted to select the lighting intervention during the autonomous mode. One user commented about the placement of the LED straps and thinks that different designs and placement will help to accept the light feedback better. We received a comment about the potential effect of the time of day (daytime or nighttime) on the appreciation of the lighting. Regarding the wind and knowing that the potential inclusion of such intervention in the real cars will be via the AC systems, one participant mentioned that the perception could be different when the driver decides to open the vehicle's windows.

A user suggested changing the direction of the wind from the face in order to be less intrusive and more subtle. Another liked the way of blowing the air in a modulated intensity. He said if it were with a constant intensity, the signal would be easily ignored, and if it were too random (like the natural wind), it would be distracting. Four participants preferred the design based on the closed-loop intervention offering an alternation between ON and OFF, compared to having the breathing intervention always ON. One argued that the wind always ON will dry his eyes while he was wearing contact lenses. Another participant felt that the conditional activation helped her to be aware of when she was "stressed." In the last driving segment, one participant experienced the "hallucination" of the auditory intervention sound even when the intervention was OFF.

6.5.3 Future Work Suggestion. A participant suggested considering the use of olfactory and tactile feedback to enhance the effect of the intervention. Another one would like to have the choice of selecting a music track as an auditory intervention to help him reach a calmer state.

7 DISCUSSION AND FUTURE WORK

This work investigated the efficacy of a just-in-time breathing intervention stimulated by multi-sensory feedback to promote calm breathing inside the car. Two randomized controlled studies were conducted using a car simulator involving a total of 55 participants. Different conditions were evaluated: the effects of multi-sensory vs. unisensory feedback, user choice, effect of the training to the intervention, and the task of manual driving vs. being driven autonomously in the efficacy of the breathing intervention. We discuss here the findings, the limitations, and future work.

One main goal of the user studies is to examine the effect of the multi-sensory stimulation compared to the unisensory in the breathing intervention efficacy. While the multi-sensory was associated with improved driving performance for the first study and maintaining the same level for the second study, the difference was not significant in terms of engagement for the participants. In fact, neither the single-modality (ambient noise) nor the multi-sensory feedback was reliably associated with calming the breathing of the participants, except under limited circumstances (namely right after training, and when the load was low.)

This finding appears to contrast with the results of Ghandeharioun and Picard [27], where ambient noise modulation was associated with lowered breathing rate and with increased self-reported calm and focus in an office setting. However, it is possible that a significant difference in demands and possibly in the user's sense-of-control for the two contexts can explain the difference in results: In the office tasks, participants could easily modulate their breathing without risk as their context was safe and largely under their control, as they were asked to read articles and answer short quizzes; however, in the simulator, the drivers did not know what was going to happen next (in terms of pedestrians, bicyclists, and other cars pulling out) and they had to be constantly vigilant to avoid hitting anyone. Also, in the present study, each driving segment consisted of five minutes, which might not be sufficient to induce breathing engagement to the intervention. In the office-based study, users were exposed to the ambient intervention for 40 to 50 minutes [27]. Further studies need to consider the context and duration of exposure to the intervention, especially the multi-factor demands placed on each participant.

In this work, the worth of providing multiple options of uni-and multi-sensory interventions existed more in the user's subjective acceptance for using it under a driving task rather than the user's breathing engagement. Comparing the user study 1 and 2, the participants reported significantly higher pleasure when given a choice of selection for the intervention modality at the beginning. Including the sensory stimulations in the present study and the in-car haptic stimulation from former studies [7, 53], there are diverse sensory modality combinations for in-car breathing intervention. It is hard to conclude one modality is superior to another. We would suggest leaving the role of choosing the best combination of intervention stimulations to the users in order to fulfill their acceptance.

The training to the intervention helped increase the drivers' engagement in the breathing guide. After the training session, the participants were expected to have a higher workload while engaging better in the intervention. However, there was no significant difference before and after the training session in the subjectively reported workload. This may be due to the fact that we asked the participants explicitly to focus on the driving task as the main task and to feel free to engage with the intervention when possible. This instruction may be the reason why the workload was not significantly increased. Also, it might be the case that explaining what the stimuli were designed to do helped decrease their uncertainty-related workload. Future work might add objective measures of the driving task load and engaging in the intervention, such as eye-related measures (e.g., pupil dilatation or blink latency) [46] while inducing different levels of workload (e.g., the delayed digit recall task (n-back) [50]).

One limitation of this work is related to the low sample size and the sampling method used here. In fact, only 26 drivers participated in the first study and 36 in the second study. We recruited drivers by sharing the recruitment material with our institution's mailing lists. We used thus one of the non-probability sampling methods, which is convenience sampling. We plan in the future to consider a stratified sampling based on gender, age ranges, and driving experience.

The non-significant difference in driving mistakes after the training of the intervention is also worthwhile to discuss. In another study, the conscious breathing intervention using a harmonic chord-based auditory signal is reported to cause an increased number of driving mistakes even with instructing the drivers on a higher priority in safe driving [75]. As stated in section 6.5, many participants mentioned that they could easily ignore the intervention signal when they wanted to focus on a driving task. The quantitative measure of driving mistakes and qualitative feedback from the participants make us think that the ambient sensory stimulation worked properly for allowing the drivers to switch their attention easily between the driving and the intervention.

A maintained acceptance accompanied the engagement in terms of the reported arousal and pleasure. However, the objective arousal reflected by the EDA was significantly different when comparing the average tonic level and the total number of peaks before and after the training session. While rise of the arousal was expected, a significantly lower number of peaks was observed after the training session. The effect of habituation to the feedback exposure may explain this reduction, as might more certainty and understanding related to the periodic stimuli. Further investigation should be conducted to confirm these findings. We can also study the effect of different types of training sessions on the engagement and arousal level, to select the best in maintaining the driving performance, improving the engagement and maintaining or improving the intervention acceptance by the drivers. Recently, the breathing exercises were deployed in different settings due to their efficiency to help reduce stress and anxiety, for example, [17, 59]. Breathing exercises have also proven their efficacy in daily routines such as practicing yoga and meditation [17, 66] or performing a work task [27] and can be integrated into wearable devices like smartwatches. This may enhance the subconscious engagement of the user in the intervention. We plan to study the effect of breathing exercise practice in the subconscious engagement in the intervention. We can include different types of stimulation, such as the haptic feedback that has been tested in (highly constrained) real-world driving [6, 7].

These study findings suggested that suppressing the driving task by offering the autonomous mode to the participants improved the subconscious engagement in the intervention (as shown by the NBR's). This leads us to think that the breathing intervention may help the vehicle's passengers or, in the future, the drivers that become passengers after the activation of the autonomous navigation mode. Based on the qualitative feedback in section 6.5.2, it is also interesting to remark that a driver's sensory stimulation preference can differ between manual and autonomous driving, especially for the visual part. Intrinsically, the driving task holds a large perception load for visual sensory though it is hard to quantify the exact amount [62]. When considering autonomous driving, which releases a substantial part of the occupied visual load from manual driving, we would suggest trying more active visual stimulation to engage a driver in the intervention. We note that we assumed the fully autonomous driving scenario in this work, which did not require a driver's attentive monitoring responsibility for a sudden driving task takeover. Stapel et al. [64] reported the unignorable workload from a group of supervised automated driving users, who are not familiar with the autonomous features and given the monitoring task of driving situation. The driver's engagement to the breathing intervention in such supervised automated driving case remains as future work.

When analyzing the engagement in terms of breathing rate per road zone, we found that being at the traffic light was associated with better engagement with the breathing guide compared to straight zone, particularly after the intervention training. This finding leads us to the potential improvement of the in-car intervention system by utilizing the driving context information as one of the control input parameters. Before confirming this finding, there exist some limitations in our study. Firstly, each participant spent insufficient time around the traffic light zone compared to the 30-second time window of breathing rate analysis. Unbalanced time duration in each zone, shown in Fig. 12, might limit a fair statistical analysis of breathing rate per each zone as well. We plan to investigate this finding more by designing a particular route where the driver encounters more than one traffic light with adequate waiting time for physiological signal analysis and each zone's data balance. If this finding is confirmed, we can then suggest turning on the intervention when waiting at the red light, stop signs, or even when stuck in the middle of traffic. As future work, we plan to analyze the driving scene and corresponding engagement levels, in order to see where higher engagement occurs naturally, and in order to better optimize timing and modalities for triggering a helpful intervention.

The user's profile, particularly the personality traits, has also been associated with an effect on driving performance and technology acceptance [44, 70, 75]. A future study may investigate the association between user personality traits and depression level on the efficacy of the intervention. On that note, we used the PHQ-9 to assess depression severity. While this questionnaire is widely used and validated for several subpopulations, with a recent meta-analysis examining more than 58 studies, it does show a higher false positive for younger participants [43]. Future assessments might ask participants if they have been diagnosed for depression and consider another questionnaire such as the Primary care Screening Questionnaire for Depression, perhaps crossing the results with the PHQ-9 scores.

Although the car simulator provided a semi- naturalistic environment, and we provided the participants with instructions and the driving training sessions, the generalization of our findings to the real-world driving context remains future work. While a field study will help to evaluate the validity of the findings in the real-world driving setting, we caution that giving drivers anything else to attend to while operating a vehicle should be done with great care and respect for the complexity and unpredictability of their situation.

8 CONCLUSION

This paper examined the efficacy of a just-in-time closed-loop breathing intervention stimulated by auditory, visual, tactile, and thermoceptive feedback to promote calm breathing inside the car. First, we investigated the effect of the multi-sensory compared to the unisensory auditory feedback in driving performance and user engagement. Different settings were considered as well to examine the effect of the user's involvement and the driving task in the driver's engagement and acceptance of the intervention. The findings show that the participants were able to engage in the breathing intervention after training them on how to match their breathing rhythms with the multi-sensory stimulation. In addition, the intervention was more efficient when the driving task was suppressed (during autonomous driving) suggesting that the breathing guide can help the passengers and the drivers in the autonomous mode with calm breathing.

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