Sequential Scent Intervention to Induce Affective Changes in High-Stress Driving Simulation

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Abstract

In safety-critical environments such as driving, sustained cognitive load and stress can degrade attention, decision-making, and performance, motivating the need for affective regulation mechanisms that operate without introducing additional cognitive demand. Existing interventions based on visual or auditory cues often compete for attentional resources, limiting their applicability in high-load contexts. This work investigates sequential olfactory intervention as an alternative, ambient modality for affective regulation during driving. We present a system that delivers personalized scent sequences and deploys them during driving and recovery phases in a high-fidelity racing simulator. We evaluate effectiveness through a multi-modal framework integrating physiological signals, behavioral observation, and self-reported rates, using a within-subject comparison against no-scent baselines. Across ten analyzable participants, sequential scent intervention produces statistically significant modulation of tonic physiological arousal, including reduced EDA variability and stabilized skin conductance levels, while exerting minimal influence on rapid phasic responses. Our findings characterize sequential olfaction as a sustained, non-distracting affective modulator and highlight the limitations of static personalization, motivating future adaptive, human-in-the-loop approaches.

1 Introduction

Optimal human performance in complex, high-stakes situations—such as competitive racing, emergency response, or air traffic control—is fundamentally limited by the ability to manage acute mental stress and sustained cognitive load. In competitive racing environments, drivers operate at the absolute limit of their physical and mental capacity, where a sustained high-stress state degrades perceptual abilities, narrows attention, and slows critical decision-making processes, directly correlating with a decrease in performance and an increased risk of error. Traditional methods, such as voice commands or visual dashboard alerts, can often be counterproductive, as they add to the very cognitive load they intend to alleviate. Therefore, there is a critical need for a non-intrusive affective regulation system that can subtly guide the operator back toward a state of focused calm. This capability is vital not only for maximizing performance in professional settings but also for improving driver mental well-being.

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Prior research into affective interventions has primarily focused on explicit sensory modalities, such as auditory cues or visual interfaces, which fundamentally conflict with the high demands of the driving task. The major challenge for real-time stress mitigation is the modality compatibility problem: how to deliver an affective intervention that is potent enough to influence emotional state but ambient enough to remain below the threshold of conscious cognitive intrusion. Existing ambient approaches, such as continuous background music or static air fragrance, lack the necessary temporal precision and dynamic responsiveness to address *acute* stress bursts effectively. Furthermore, current systems often rely on a one-size-fits-all approach to scent, failing to account for individual physiological variability and personalized affective responses to different odors, which can be highly subjective and even aversive. Specifically, the literature lacks a robust framework for dynamically selecting and sequentially delivering personalized ambient cues in response to real-time physiological stress indicators, creating a gap in the design of truly adaptive and personalized affective systems.

In this paper, we present a Sequential Scent Intervention system deployed in a high-fidelity driving simulator to investigate ambient olfaction as a non-intrusive modality for affective regulation under sustained cognitive load. Through a within-subject comparison between driving with and without scent intervention, we empirically examine how sequential olfactory stimuli influence drivers' physiological and subjective states.

Our results show that sequential scent intervention does not attenuate rapid, event-related stress responses (phasic activity), but instead operates as a sustained affective layer, significantly modulating tonic physiological arousal over longer temporal scales during both driving and recovery phases. Notably, we observe a consistent physiological–subjective dissociation, in which robust changes in tonic arousal (e.g., reduced skin conductance level and improved heart rate variability) occur despite participants reporting only modest conscious awareness of emotional change. This suggests that olfactory intervention functions as a largely subliminal and non-distracting regulator, well-suited for attention-critical contexts. At the same time, responses to scent intervention exhibit clear inter-individual variability, with participants showing qualitatively different modulation patterns. This heterogeneity highlights the limitations of static, rule-based personalization and motivates adaptive, human-in-the-loop approaches for ambient affective computing.

Our contributions are threefold:

- We provide empirical evidence that sequential scent intervention selectively modulates sustained, tonic physiological arousal, supporting both stress regulation and recovery in high-load driving contexts.
- We demonstrate that olfactory modulation can produce measurable physiological benefits without requiring conscious emotional awareness, positioning scent as a uniquely non-intrusive affective modality.
- We identify personalization limits in rule-based scent sequencing and outline a path toward human-in-the-loop reinforcement learning for adaptive ambient intervention systems.

2 Related Work

High-stress, attention-demanding scenarios, such as competitive driving, present a unique set of challenges that can lead to severe cognitive overload and compromise safety. Race car drivers operate under extreme psychological pressure can be exposed to psychiatric risk factors Colangelo et al. [2024]. This environment necessitates interventions that address not only alertness level but also sustained affective stability that supports both the driver's psychological state as well as their physical wellbeing. Traditional approaches to information delivery in vehicles often involve explicit modalities such as visual displays and voice-based instructions. However, in high-stress driving scenarios, these modalities force the driver to engage in task switching and divert visual-focal attention, increasing cognitive load and potentially leading to performance errors and accidents Stephan et al. [2021].

2.1 Scent as a Modality for Affective Change

The ability of scent to influence human physiological and psychological states is well-established, largely due to the direct anatomical connection between the olfactory bulb and the limbic system, the brain's center for emotion and memory. Research has consistently demonstrated that scents can modulate human psycho-physiological activity. For example, specific fragrances have been shown to influence electroencephalographic (EEG) responses and physiological arousal Sowndhararajan and Kim [2016] Furthermore, olfactory stimuli have been shown to function in implicit emotion regulation during emotional processing tasks, suggesting they can operate beneath the threshold of conscious awareness Cai et al. [2025].

Studies have explored the use of a singular scent for targeted affective outcomes in driving. For instance, in-vehicle peppermint fragrance has been utilized to actively maintain driver's alertness Mahachandra et al. [2015]. The paper highlights its limitations in the comparison results that "Less dosage could result in nothing, whilst longer exposure might end up in drivers' immunity. With intermittent method of exposure, ones must make sure that the duration still results in alertness rise." While these studies confirm the utility of specific scents for singular outcomes (e.g., increased alertness), they often rely on continuous exposure, which is susceptible to desensitization. Such desensitization is well-investigated process and can be found across all sensory modalities. Li et al. [2023] For scent specifically, the desensitization enhances human ability to detect new stimuli from background scent, likely as a way to identify potential life threatenining odors. However, this means that the consistent continuous scent affectiveness can wear out quickly. Therefore, our novelty lies in addressing this desensitization effect.

2.2 Olfactory Interfaces in Driving and HCI

A growing body of HCI research has been exploring scent as a non-visual, non-auditory modality ideally suited for environments like driving, where the visual and auditory channels are prioritized for safety-critical tasks and scent is used as an ambient display. Prior studies have shown that olfactory stimuli can convey information without interrupting focal perception Dmitrenko et al. [2018]. In Dmitrijis Dmitrenko et al's study, I Smell Trouble: Using Multiple Scent to Convey Driving-Relevant Information, their findings demonstrate that olfactory notification are perceived as less distracting, more comfortable, and more helpful than visual notifications when it comes to giving driving directions.

Recent studies have focused on developing and evaluating scent interfaces for conveying complex state information. Systems like CARoma Therapy explored using pleasant scents to promote safer driving and improved mood in high-arousal drivers Dmitrenko et al. [2020]. Other work has focused on the technical delivery and meaningful use of scent, comparing various scent-delivery devices and validating scent-notification pairings for in-car interaction Dmitrenko et al. [2016]. Projects have also used scent as a means of monitoring and communicating the status of automated driving systems, such as S(C)ENTINEL, which used olfactory displays to convey information that were deemed more trustworthy Wintersberger et al. [2019].

Building on top of their findings, we decided to analyze deeper how in stressful driving scenarios this specific scent information display can be especially useful and stress reducing. We began by looking at the different sensory modalities a driver is tuned into at any given time multiple modalities. They are on autopilot where their body is reacting to the environment almost by nature in flow state. During this state, their body is tuned to all the environmental stimuli, the coming visual information, the sound of the wind, the tactileness of the car, we position these as ambient information. Thus, the stress arise when drivers are taken out of this ideal state of mind. When a sudden voice interjection might take them out of their flow state. As Stephan et al. [2021] study have shown, the cost of task switching across compatible modalities vs. incompatible modalities is quite high. We believe that by having the drivers switch between these ambient modalities that are more compatible, scent can carry information without causing information overload Dmitrenko et al. [2019].

Prior work has successfully validated scent as a less distracting informational and affective modality in driving and has begun exploring its use to promote safety or specific emotional states (e.g., alertness). However, these interventions predominantly rely on the use of singular scents or simple, non-dynamic olfactory signals.

To our knowledge, this paper is the first to evaluate the effectiveness of sequential scent intervention on people's affective and physiological changes in a sustained, high-stress and attention-demanding simulated driving scenario. By actively changing the scent sequence, our approach directly addresses the fundamental limitation of desensitization associated with continuous ambient scent exposure. We demonstrate that this dynamic intervention has the potential to maintain sustained effectiveness in managing cognitive load and affective stability, and we believe our approach can be expanded to other high-stress and attention-demanding scenarios where sustained, non-intrusive affective regulation is critical.

3 Problem Statement

This work investigates the effectiveness of sequential scent intervention in a high-stress driving context. Specifically, we ask: **What is the effectiveness of sequential scent intervention in driving tasks that demand continuous attention?** And more specifically, how can we define, measure, and evaluate such effectiveness? Addressing this question requires moving beyond single subjective measures and instead examining effectiveness through a multimodal lens, incorporating physiological signals, behavioral observation, and self-reported experience.

We further explore what constitutes a sequential scent intervention in practice: how multiple scents can be composed, ordered, and delivered over time as an ambient feedback channel, and how such sequences may be tailored to individual users. Based on prior findings linking olfaction to emotional arousal, we hypothesize that **a well-designed personalized sequential scent intervention can support driving performance by (1) reducing excessive emotional arousal, and (2) maintaining a state of focused engagement during high-stress driving tasks.**

4 Proposed Method

To address the challenges outlined in the problem statement, we propose a methodological framework that combines multimodal evaluation of affective effectiveness with a comparative, human-in-the-loop approach to personalized sequential scent design. Our method is designed to operationalize the notion of effectiveness in high-stress driving contexts and provide a scalable entry point for generating personalized scent interventions.

4.1 Multimodal Evaluation of Effectiveness

We conceptualize the effectiveness of sequential scent intervention as a multidimensional construct, rather than a single outcome measure (see Figure 1. Specifically, our approach evaluates effectiveness through the integration of three complementary modalities: physiological signals, behavioral observations (collected by researchers), and self-reported experiences (from participants).

Physiological data, such as electrodermal activity (EDA) and breathing patterns, provide continuous and implicit measures of emotional arousal and regulation during driving. Behavioral observations capture visible signs of engagement, discomfort, or disruption (e.g., motion sickness or task interference), which may not be fully reflected in physiological signals alone. Self-reported data offer subjective assessments of emotional state, stress level, and perceived scent effectiveness, grounding the analysis in the participant's lived experience.

By triangulating across these modalities, our framework moves beyond single-metric evaluation and enables a more in-depth assessment of whether and how sequential scent interventions influence affective states during high-stress, attention-demanding tasks.

4.2 Comparative Scent Annotation for Personalized Sequential Design

To produce personalized scent sequences, we introduce a comparative annotation strategy that captures individual differences in olfactory-induced arousal. Rather than relying on absolute ratings, participants compare pairs of scents along an arousal dimension (e.g., more energizing versus more calming), allowing us to derive a relative ranking for each individual.

This comparative ranking is then used to generate two types of personalized scent sequences: an arousing sequence composed of higher-ranked scents, and a calming sequence composed of lower-ranked scents. These sequences form the basis of the sequential scent intervention delivered during two different phases of the task, driving and calming.

Importantly, this approach serves not only as a practical method for personalization, but also as a foundation for constructing a scent–emotion embedding, where relative relationships between scents

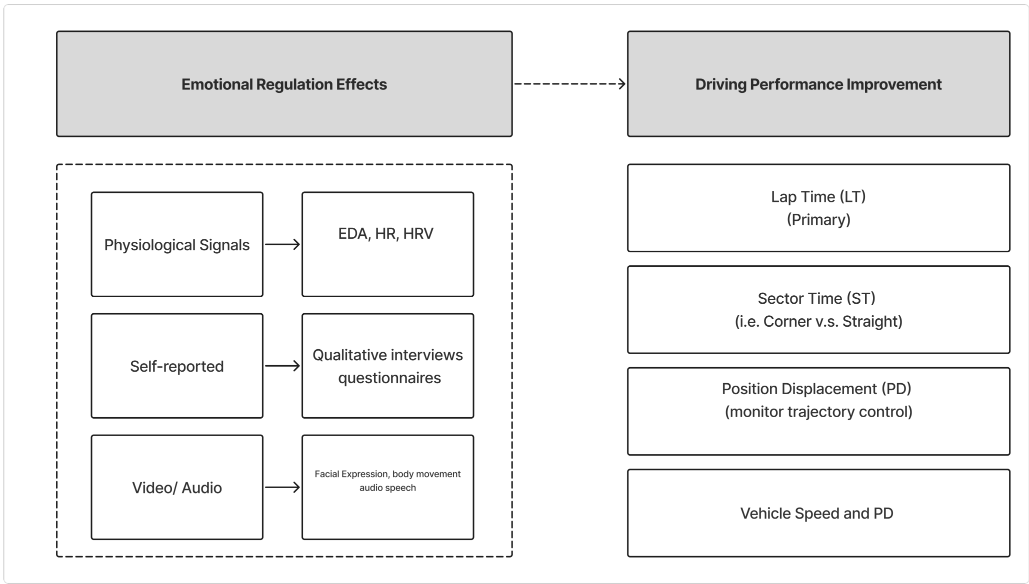

Figure 1: Multimodal evaluation framework for sequential scent intervention.

and affective responses are explicitly represented. While this rule-based personalization provides a lightweight and interpretable starting point, it also exposes the limitations of relying solely on pre-task subjective annotation, motivating later experimental designs toward adaptive, human-in-the-loop optimization, which we will discuss in Section 8.2.

5 Experimental Methodology

To instantiate and evaluate the proposed framework, we designed a controlled user study situated in a simulated high-stress driving environment. This experimental setting allows us to systematically deploy personalized sequential scent interventions while maintaining practical control over task conditions, scent delivery, and data collection. Given the practical and safety constraints of conducting studies in real-world racing contexts, a driving simulator provides a viable and ecologically relevant approximation of high cognitive load and attentional demand.

Within this setting, we integrate a wearable scent delivery device with continuous physiological sensing, behavioral observation, and post-task self-report measures. Personalized scent sequences generated through comparative annotation are delivered during distinct phases of the driving task, enabling within-subject comparisons between scent and no-scent conditions, followed by cross-participants validation. Together, this experimental design allows us to examine how sequential scent interventions influence affective arousal and focus during driving.

5.1 Participant Demographic

We conducted a total of 22 user study sessions. (Please see data in appendex) Of these, data from 10 participants were included in the core analysis. The remaining sessions were excluded based on predefined inclusion criteria related to study consistency, data completeness, and potential bias.

Specifically, nine sessions were excluded due to methodological variations introduced during early pilot phases (including voice-based intervention, single-scent conditions, or the absence of a calming phase). One session was excluded due to severe motion sickness induced by the combination of scent and driving, which prevented completion of the study. Two sessions were excluded due to participants' prior knowledge of the study goals, which could introduce expectation bias.

The final dataset consisted of 10 participants (age range: 20–55 years), with five identifying as female and five as male. All participants reported normal olfactory function and no history of severe

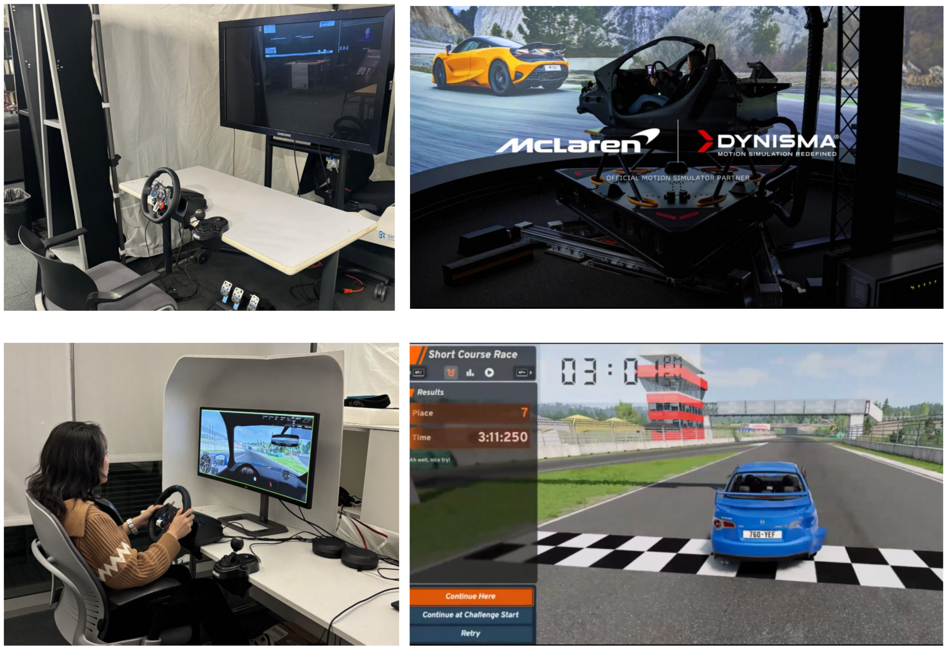

Figure 2: **Racing simulation setup.** Top-left: desk-mount fixed-base racing simulator used for the primary user study, including steering wheel, pedals, and single-display visual output. Top-right: reference image of a high-fidelity commercial motion simulator, shown for contextual comparison of simulator realism (not used in the study). Bottom-left: participant performing the driving task in the experimental setup, seated in front of a partial enclosure to reduce peripheral visual distractions. Bottom-right: in-game racing environment and task outcome screen illustrating track layout, traffic conditions, and lap completion feedback.

motion sickness. They were further categorized into two experience-based persona groups based on their self-reported driving and racing background, which later informed the interpretation of both behavioral and physiological results:

- "Racer" Persona (Experienced): Participants with prior experience in high-fidelity racing simulators or real-world racing. These participants generally demonstrated greater familiarity with high-speed driving tasks and were often able to maintain a focused and composed state during the driving task.
- "Novice" Persona (Inexperienced): Participants with limited or no prior experience with racing simulators or high-demand driving tasks. This group tended to report higher perceived stress and difficulty maintaining calmness during the driving task.

5.2 Experimental Setup

Driving Simulation Environment: The experiment was conducted in a dedicated driving simulation environment designed to induce sustained cognitive load and emotional arousal. Participants performed a high-speed driving task using a Logitech G29 driving simulation wheel and pedal system, paired with a high-fidelity racing simulation game running on BeamNG.drive. All participants drove on the same track under identical visual and mechanical settings to ensure comparability between the scent and no-scent conditions.

Sequential Scent Delivery System: Sequential scent interventions were delivered using a custom-built wearable scent device worn as a neck band (see Figure 2 right). This form factor positions scent delivery close to the participant's breathing zone while minimizing obstruction to vision, hearing, or

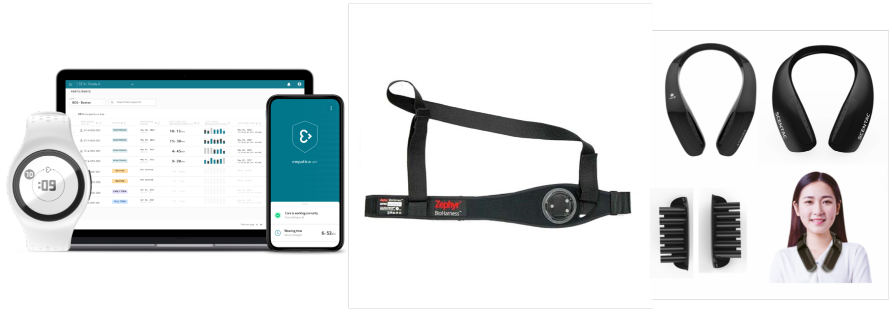

Figure 3: **Physiological sensing and intervention setup.** Left: Empatica wearable ecosystem for electrodermal activity (EDA), temperature, and motion sensing; Middle: Zephyr BioHarness chest strap for heart rate variability (HRV) and respiration signals; Right: neck-worn scent delivery device used to program olfactory interventions during driving.

motor control. The device functions as an ambient intervention modality, operating continuously in the background without requiring explicit user interaction or attentional shifts.

The device supports the release of multiple discrete scent types in a sequence. For this study, a set of 12 perceptually distinct base scents was selected to span a broad affective range. To reduce confounding factors and isolate the effect of scent type and sequence, the intensity and release duration of each scent were kept constant across participants and conditions. Each scent was released for approximately 40–60 seconds. The scent device was programmatically synchronized with the experimental timeline, allowing precise control over when scent sequences were presented during the driving and calming phases. In the no-scent baseline condition, the device was worn but inactive, ensuring that any observed effects were attributable to scent intervention rather than the presence of the hardware itself.

Physiological and Behavioral Data Collection: Physiological responses (including EDA, BVP, and skin temperature) were continuously recorded throughout the experiment using an Empatica Plus wristband worn on the non-dominant hand. The sensor was attached prior to the task and remained active during baseline, driving, calming, and recovery phases. EDA was selected as the primary physiological signal due to its established relationship with sympathetic nervous system activation and emotional arousal. For a subset of participants (4 out of 10), respiratory signals were additionally recorded to capture breathing rate as complementary indicators of affective and regulatory states. All physiological signals were time-synchronized with task events and scent delivery markers to enable phase-based and condition-based analysis.

In addition to physiological data, behavioral observations and task performance logs from the driving simulator were recorded to contextualize participants' physiological responses. Subjective self-reported measures were collected separately using post-task questionnaires.

5.3 User Study Design and Procedure

5.3.1 Study Design

The study followed a within-subject experimental design to evaluate the effect of sequential scent intervention on participants' affective states during a high-demand driving task. Each participant experienced two primary conditions: (1) a no-scent baseline condition (ScentNONE) and (2) a personalized sequential scent intervention condition (ScentSEQ).

In both conditions, participants performed the same driving task on the same simulated track, followed by a calming period. The order of the two conditions was counterbalanced across participants to mitigate potential order and learning effects. This design allows direct comparison of physiological and subjective responses under scent and no-scent conditions while accounting for large inter-individual variability in baseline arousal.

5.3.2 Scent Annotation and Personalization

Prior to the driving task, participants completed a scent annotation process to enable personalization of the sequential scent intervention. A set of **12** perceptually distinct base scents was presented to each participant. Participants were asked to perform a comparative ranking task based on perceived emotional arousal, responding to prompts such as: *"Between Scent A and Scent B, which one makes you feel more excited or energized versus more calm or relaxed?"*

Although multiple affective dimensions (e.g., valence, dominance, refreshing) were initially considered, pilot testing revealed that extended multi-dimensional olfactory annotation led to perceptual fatigue and diminished discrimination. To balance annotation quality, session duration, and participant comfort, each user study session focused on a single affective dimension. **Arousal** was prioritized as it directly relates to the study's core research question and aligns closely with tonic electrodermal activity (SCL), enabling cross-modal comparison between subjective assumption and physiological measures.

Based on each participant's arousal ranking, a personalized sequential scent intervention was generated using a rule-based approach. For the driving phase, the three scents ranked as most arousing were selected and released sequentially. For the calming phase, the three scents ranked as most calming were selected and released sequentially. Each scent was presented for a fixed duration of approximately 50 seconds, with consistent intensity across participants.

5.3.3 Study Procedure

Each user study session lasted approximately **60** minutes and followed a standardized protocol (see Figure 4):

Upon arrival, participants provided informed consent and were fitted with physiological sensors. A 3–5 minute resting period was conducted prior to the task to establish an individual baseline for subsequent normalization of physiological signals. Participants then completed a 15-minute warm-up and familiarization phase, during which they drove several laps on the simulated track to acclimate to the driving controls, visual environment, and overall task dynamics.

Following this, participants completed both experimental conditions:

- **Baseline Condition ($\mathbf{Scent_{NONE}}$):** Participants performed the driving task for a designated duration (two laps) without any scent intervention, followed by a three-minute calming period. The scent delivery device was worn but inactive. Time-based annotations marked the onset and offset of the driving and calming phases, as well as unexpected situations encountered along the way (such as collisions, loss of control, or going off the track).
- **Sequential Scent Condition ($\mathbf{Scent_{SEQ}}$):** Participants repeated the same driving task and calming period while exposed to their personalized sequential scent intervention. Scent delivery was synchronized with the experimental timeline and phase annotations.

After completing each condition, participants filled out a short self-report questionnaire assessing perceived stress, emotional state, and subjective driving experience using a 7-point Likert scale. At the end of the session, a semi-structured exit interview was conducted to gather qualitative feedback on scent perception, comfort, perceived effectiveness, and any adverse experiences such as discomfort or motion sickness.

5.4 Evaluation Metrics and Data Analysis

To evaluate the effectiveness of sequential scent intervention, we adopted a multimodal measurement and analysis approach combining physiological signals, subjective self-reports, and task-phase annotations. All analyses were conducted at the within-subject level and later examined across participants.

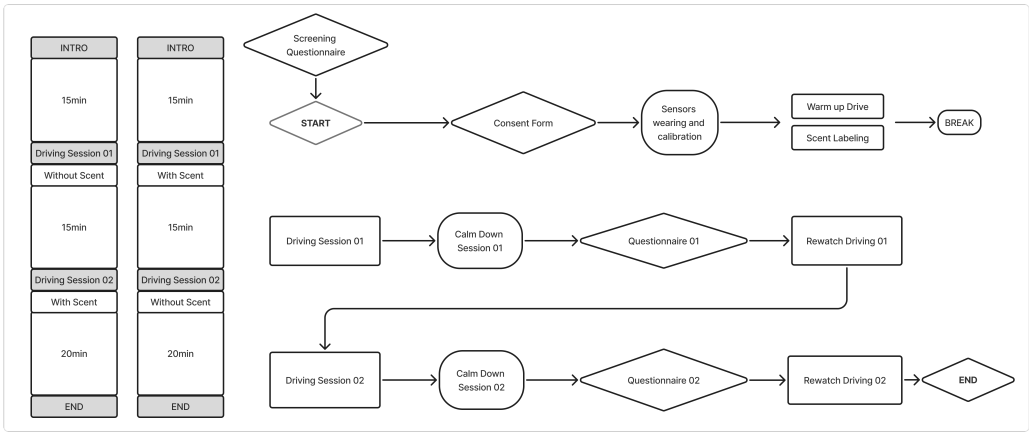

Figure 4: User study flow

5.4.1 Physiological Measures

Electrodermal activity (EDA) served as the primary physiological indicator of emotional arousal. To account for large inter-individual variability in baseline skin conductance, each participant's EDA signal was normalized relative to their individual resting baseline collected before the driving task. Following preprocessing, we decomposed EDA signals into tonic and phasic components using NeuroKit2. The tonic component, Skin Conductance Level (SCL), reflects slow-varying baseline arousal, while the phasic component, Skin Conductance Response (SCR), captures rapid, event-related arousal fluctuations. This decomposition enables separate analysis of overall arousal level and moment-to-moment reactivity or distraction.

For participants with available respiratory data, breathing amplitude and variability were additionally computed to provide complementary indicators of affective regulation and physiological stability. Due to incomplete availability across participants, respiratory measures were treated as secondary signals and analyzed when present.

Phase-Based Segmentation. All physiological signals were segmented according to predefined experimental phases, including driving and calming periods under both ScentNONE and ScentSEQ conditions. Phase boundaries were determined using time-stamped annotations recorded during the experiment and aligned with physiological data streams. This phase-based segmentation enables direct comparison of physiological responses within equivalent task contexts, isolating the effect of scent intervention from task-related variability.

Feature Extraction. From the segmented physiological signals, we extracted summary features commonly used in stress and affective state analysis. For each participant and experimental phase, we computed:

- **Mean tonic arousal:** average normalized SCL value, representing overall arousal level.
- **Mean phasic arousal:** average normalized SCR value, reflecting transient reactivity.
- **Arousal variability:** standard deviation of normalized EDA signals, capturing the stability or volatility of physiological arousal over time.
- **Respiratory features (when available):** mean breathing amplitude and breathing variability.

These features were computed separately for each phase (e.g., driving with scent, driving without scent, calming with scent, calming without scent) to support within-subject comparisons. Figure 5 shows an overview of plotted data from two participants

5.4.2 Subjective Measures

After each experimental condition, participants completed a short self-report questionnaire assessing perceived stress, emotional state, and driving experience using a 7-point Likert scale. These subjective

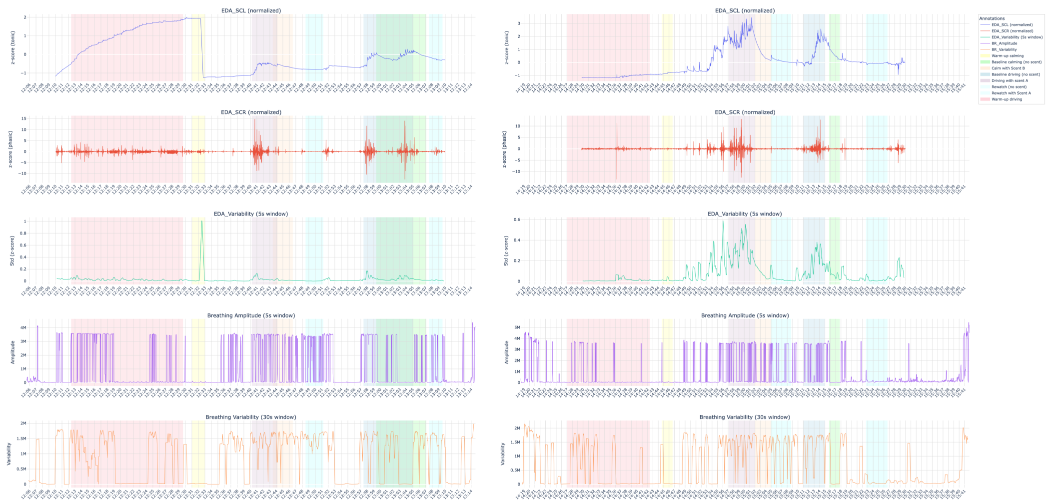

Figure 5: Physiological data plot of two participants (left and right)

measures provide qualitative and quantitative context for interpreting physiological responses and help capture experiential aspects not directly observable in biosignals. We mapped these rating scores with the calculated physiological features across different phases.

5.4.3 Statistical Analysis

Given the small sample size and non-normal distribution of several physiological features, we employed non-parametric statistical tests. Specifically, Mann–Whitney U tests were used to compare summary features between scent and no-scent conditions for each participant and experimental phase. Statistical significance was assessed at an alpha level of 0.05. In addition to within-participant analyses, patterns were examined across participants to identify consistent trends and inter-individual differences, including distinctions between experienced ("Racer") and inexperienced ("Novice") driver personas. These cross-participant observations are reported descriptively and further discussed in the next section.

6 Results and Discussion

6.1 Overall Effect of Sequential Scent Intervention

Across the 10 participants included in the final analysis, sequential scent intervention demonstrated a consistent impact on physiological indicators of emotional arousal during both the driving and calming phases. Compared to the no-scent baseline condition (ScentNONE), participants exposed to personalized sequential scent (ScentSEQ) exhibited significant differences in tonic electrodermal activity (SCL) and arousal variability across experimental phases.

Table 1 summarizes the mean normalized EDA measures by condition and phase of two participants. Statistical comparisons using Mann–Whitney U tests (see Table 2) reveal that, for the majority of participants, both driving and calming sessions under $\text{Scent}_{\text{SEQ}}$ differed significantly from their corresponding no-scent baselines. Notably, these effects were observed not only during the high-demand driving task but also during the subsequent calming period, suggesting that scent influenced both stress regulation and recovery processes.

6.2 Scent as a Sustained Modulator of Affective State

Statistical results (Table 2)also reveal a clear dissociation between tonic and phasic physiological responses. Across experimental phases, sequential scent intervention significantly influenced tonic arousal, particularly during the driving phase. In contrast, SCR measures that capture rapid, event-related responses on the order of one to several seconds did not differ reliably between conditions.

Table 1: Summary of EDA and breathing mean values across phases.

Phase	**SCL$_{mean}$**	**SCR$_{mean}$**	**EDA$_{var}$**	**BR$_{amp}$**	**BR$_{var}$**
Participant ID: 01					
drive$_{scent}$	2.047 (H)	-0.003	0.292 (H)	2069171.586 (H)	1399591.312 (H)
drive$_{no\ scent}$	0.848 (L)	0.000	0.175 (L)	1835870.631 (L)	1373782.991 (L)
calm$_{scent}$	0.691 (H)	0.004	0.084 (H)	1127739.230 (L)	1286576.394 (H)
calm$_{no\ scent}$	0.625 (L)	0.001	0.068 (L)	140932.264 (H)	254760.315 (L)
Participant ID: 02					
drive$_{scent}$	-0.620 (L)	0.002	0.041 (L)	2462363.407 (L)	1366247.110 (H)
drive$_{no\ scent}$	-0.249 (H)	0.009	0.070 (H)	2566815.144 (H)	1294133.723 (L)
calm$_{scent}$	-0.627 (L)	0.000	0.016 (L)	1602086.839 (H)	1499989.344 (H)
calm$_{no\ scent}$	-0.075 (H)	-0.001	0.032 (H)	604082.68 (L)	871132.559 (L)

Table 2: Mann–Whitney U test results comparing scent and no-scent conditions across phases.

Phase	**SCL$_{mean}$**	**SCR$_{mean}$**	**EDA$_{var}$**	**BR$_{amp}$**	**BR$_{var}$**
Participant ID: 01					
Drive_scent	U=58444.00	U=36635.00	U=52989.00	U=47376.50	U=31369.00
vs	p=0.00000	p=0.33715	p=0.00000	p=0.00000	p=0.04223
Drive_no_scent	**Sig.**	N.S.	**Sig.**	**Sig.**	**Sig.**
Calm_scent	U=10979.00	U=11845.00	U=13372.00	U=21111.50	U=20519.00
vs	p=0.45816	p=0.70972	p=0.01934	p=0.00000	p=0.00000
Calm_no_scent	N.S.	N.S.	**Sig.**	**Sig.**	**Sig.**
Participant ID: 02					
Drive_scent	U=4587.00	U=11342.00	U=5315.00	U=11291.50	U=9075.00
vs	p=0.00000	p=0.89345	p=0.00000	p=0.84203	p=0.00216
Drive_no_scent	**Sig.**	N.S.	**Sig.**	N.S.	**Sig.**
Calm_scent	U=0.00	U=42736.00	U=17092.00	U=53667.50	U=64325.00
vs	p=0.00000	p=0.88130	p=0.00000	p=0.00000	p=0.00000
Calm_no_scent	**Sig.**	N.S.	**Sig.**	**Sig.**	**Sig.**

Sig. indicates $p < 0.05$; N.S. indicates not significant.

This pattern suggests that scent does not suppress immediate reactions to acute stimuli (e.g., crashes or sudden obstacles), but instead modulates background arousal over longer temporal scales spanning tens of seconds to minutes.

6.3 Physiological–Subjective Dissociation and Subliminal Effects

Despite robust physiological differences between scent and no-scent conditions, self-reported measures of stress and emotional state often showed weak or inconsistent changes at the individual level. In several cases, participants reported little conscious awareness of emotional modulation even when their physiological signals indicated substantial shifts in tonic arousal and variability.

However, a closer examination of questionnaire distributions revealed more subtle effects. Compared to the no-scent condition, sessions with scent showed fewer extreme negative emotional ratings (e.g., anxiety and frustration) and a more evenly distributed range of moderate emotional states, including calmness and mild positive affect. Self-reported stress levels similarly shifted away from extreme values toward more moderate ratings under Scent$_{SEQ}$.

Participants' ratings of scent effectiveness in calming them down were modest on average (M = 3.6 on a 7-point scale), suggesting that the intervention functioned as a gentle regulatory influence rather than a strongly perceptible calming tool. This physiological–subjective dissociation highlights the limitations of self-report measures in capturing gradual, background affective shifts. Olfactory interventions, unlike visual or auditory cues, may operate largely below the level of focused attention, shaping emotional state without producing strong introspective signals. These findings underscore the importance of physiological sensing for evaluating ambient affective interventions.

6.4 Individual Differences: Reducers, Enhancers, and Failure Cases

While the overall trend supports the effectiveness of sequential scent intervention, individual responses varied substantially. Within-subject comparisons revealed two distinct response patterns. For some participants, exposure to $\text{Scent}_{\text{SEQ}}$ resulted in reduced tonic arousal and lower physiological variability relative to the no-scent baseline. These reducers exhibited responses aligned with the intended calming and stabilizing effects of the intervention.

In contrast, other participants showed increased arousal or greater variability under scent exposure. These enhancers appeared to experience scent as distracting rather than regulating. Qualitative feedback and temporal signal patterns suggest several contributing factors, including frequent scent switching, mismatches between scent characteristics and task demands, and unintended associative or sensory overload effects.

Questionnaire responses further revealed substantial sources of noise unrelated to emotional intervention. Participants frequently attributed heightened stress to driving mechanics and interaction breakdowns, such as difficulty maintaining driving lines, navigating sharp turns, responding to simulated traffic behavior, or dealing with hardware-related issues (e.g., unstable steering, delayed system responses). These factors often dominated perceived stress, underscoring that a significant portion of arousal originated from task and system constraints rather than affective context alone.

These "failure" cases highlight the limitations of rule-based, one-shot personalization derived from static subjective rankings. While comparative annotation captures individual preferences, it does not account for dynamic task context, adaptation over time, or evolving physiological responses. The presence of enhancer patterns emphasizes the need for smoother transitional design and adaptive personalization strategies that respond to real-time feedback. This insight directly motivates our future exploration of human-in-the-loop and reinforcement learning–based approaches that iteratively refine scent sequencing using continuous physiological and behavioral signals.

7 Ethics Statement

The research protocol for this study was reviewed and approved by the Committee on the Use of Humans as Experimental Subjects (COUHES) and underwent multiple iterations to meet the standards of participant safety and ethical conduct.

7.1 Participant Safety and Autonomy

A primary ethical consideration was to mitigate the harm within the experimental design, despite the deliberate choice to induce a state of temporary, high-cognitive load stress for experimental purposes. Safety in the study was paramount; the stress induction was confined entirely to a high-fidelity driving simulator environment, which ensured that no participant was ever exposed to the physical dangers inherent in real-world high-stress driving or any potential long-term physical impact associated with hazardous environments. Furthermore, Right to withdraw was maintained through full participant autonomy, clearly articulated and frequently reiterated by informing them via the consent form and verbally that they could stop the experiment at any time, for any reason, without penalty or loss of compensation. Finally, the stress was designed to be Temporary and contained, limited solely to the designated high-cognitive load driving phases. Crucially, the experimental protocol included a structured two-minute "calm down" period following each stressful driving session, which was specifically designed and proven to help participants quickly and safely return to a neutral baseline physiological and emotional state.

7.2 Ethical Considerations of Scent Intervention

Deploying ambient sensory modalities such as olfaction introduces unique ethical considerations, particularly regarding participant comfort, involuntary exposure, and cognitive control. Although the proposed sequential scent intervention employs an ambient modality that is generally perceived as less intrusive than abrupt visual or auditory cues, the possibility that sudden scent transitions could be experienced as jarring, distracting, or cognitively intrusive remained a potential risk. To monitor these effects, participants' subjective experiences were assessed through post-session self-report questionnaires.

Despite using pre-screened scents and generating personalized sequences based on individual preference rankings, the intervention occasionally led to discomfort and unintended negative responses. Specifically, a small subset of participants (3 out of $N = 22$) reported sensations akin to motion sickness, which they subjectively attributed to changes in scent during the driving task. In addition, due to the strong association between olfaction and episodic memory, a minority of participants (2 out of $N = 22$) reported that certain personalized scents unexpectedly triggered aversive or negative memories. These observations highlight the inherent variability and unpredictability of individual olfactory responses, underscoring the importance of cautious deployment, continuous monitoring, and opt-out mechanisms when introducing ambient scent interventions in high-demand or safety-critical contexts.

7.3 Future Deployment and Scaling Ethics

Considering the eventual research vision to deploy this sequential scent intervention system in real-world contexts (e.g., race car training, daily driving), scaling the system demands robust ethical safeguards. The primary goal is to avoid Cognitive Overload: while scent is less distracting than explicit modalities, future development must establish rigorous, validated thresholds for the frequency, duration, and intensity of scent delivery to ensure the sequence remains purely ambient, minimizing the potential for cognitive distraction that could be detrimental in high-stakes scenarios. Furthermore, the system relies on highly personalized physiological and preference data, meaning strong Privacy and Personalization safeguards, including data privacy and anonymization, must be employed to protect the sensitive nature of physiological signals and emotional states. Lastly, in a real-world setting, the risk of Involuntary Exposure must be addressed. In a shared vehicle or public training scenario, non-consenting individuals (passengers, team members) must be protected, requiring future engineering to focus on developing targeted delivery mechanisms (e.g., personalized diffusion zones) to ensure that only the opt-in user receives the intervention.

8 Conclusion and Future Directions

In this paper, we presented a novel sequential scent intervention system designed to proactively mitigate stress-induced negative affect in a high-stress driving simulation. Our main contribution is the development of a personalized, physiologically-driven olfactory delivery strategy that successfully induced measurable shifts toward an altered affective state, demonstrating the potential of dynamic ambient sensory intervention for real-time emotional regulation. However, the current approach has limitations, primarily stemming from the inherent challenges of olfactory response, including the observed instances of temporary motion sickness and the unexpected triggering of negative memories in a minority of participants. Furthermore, the system is validated only in a simulated environment. Future research will focus on transitioning this concept to real-world vehicular platforms using non-contact, robust physiological sensing. This includes developing optimized, spatially-targeted scent delivery mechanisms to prevent involuntary exposure and further investigating personalized scent sequencing models to actively pre-empt and resolve individual adverse sensory responses.

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A Appendix / Supplemental Material

[Pre-Screening Quetionnaire]

section 01: General Information Question 01: Age Question 02: Geneder Question 03:Occupation/Career Question 04:Driving experience(in years)

Section 02: Racing Experience Question 05: Have you driven competitively before? Options:

- Yes, on a race track
- Yes, in a simulator
- Yes, in both a race track and a simulator
- Yes, in a video game
- No, I have not driven competitively before

Question 06: How frequently do you race competitively? Option:

- Multiple times a week
- Once a week
- Once a month
- Once a year
- Once every 5 years

Question 07: How often do you experience stressful racing situations?

- Rarely
- Occasionally
- Frequently
- Often
- Always

Section 3: Mood Patterns While Racing Question 08: On a scale from 1 to 5, how would you rate your typical mood while racing? (01 very negative, 7- very positive)

Question 09: What emotions do you typically experience while racing? (Check all that apply)options: Calm, Happy, Anxious, Frustrated, Angry, Indifferent, Other_

Question 10: Do you use any strategies to manage your emotions while racing? (e.g., music, breathing exercises, scent and fragrances) Options: Music, Breathing Exercise, Scent, Incar Fragrances, other

Question 11: How would you rate your emotional state right now (1- very negative, 7 - very positive)

Section 4: Additional Comments

Is there anything else you would like to share about your racing experience or emotional state while driving?

[Post-session Questionnaire]

section 01 Emotional State

Question 01:How would you rate your emotional state during the driving simulation? (listed rate from 1-7, 1 - very negative, 7 - very positive)

Question 02: What emotions did you experience during the simulation? (Check all that apply)

options: Angry, Anxious, Frustrated, Calm, Happy, Surprised, Other (open text)

Question 03 Did the emotion(s) change overtime? If so, how? (Open text)

Question 04: On a scale of 1 to 7, how intense was your stress during the simulation? (1 = Not at all intense, 7 = Extremely intense)

Section 2: Experience with the Simulation Question 05: How realistic did you find the driving situation? (options: Very unrealistic, somewhat unrealistic, neutral, Somewhat realistic, very realistic) Question 06: Did you encounter any scenarios that made you feel particularly stressed? If yes, please describe.

Section 3: Feedback on the Scent Intervention (For Experimental Group Only) Question 07: Did you notice any scent intervention during the session? (Option: Yes or No) Question 08: Did you recognize any particular scent? (Option: Yes or No ,Didn't notice) Question 09: Which aspects of the scent intervention did you notice? (Check all that apply)

- The characteristics and type of the scent (e.g., if it was pleasant, natural vs. artificial).
- The intensity or concentration of the scent (e.g., if it was strong, faint, or just right).
- The timing and dynamics of the scent (e.g., if it was continuous, intermittent, or changing in sequence).
- The relationship to the context of the driving simulation (e.g., if it felt random or related to my status/game events).
- The subjective effect or impact the scent had on me (e.g., if it helped me relax/focus).
- Other

Question 10: How would you rate the effectiveness of the scent intervention in calming you down?

1 = Not effective

7 Very Effective

[Post-session Interview Questions]

Question 01: Do you think the scent intervention has any impact on your driving behavior, or emotion, etc.? If so, how?

Question 02: Do you think the scent intervention affects your focus level? And how? (more focused vs distracting)

Question03: Compare the two rounds, which one do you think you perform better? And why?

Question 04: Any comments on the scent intervention? (scent type, duration, etc.)

Question 05: If you were invited to our final racing challenge, would you like to use any scent intervention or not? And why?

Question 06: When watching your recording, was there scent in the first or second recording? Which one do you remember?

Question 07: What was your arousal level during the watching was there a difference between the first time and second time?