Before Demand Peaks: Event-Relative Onset Timing of Implicit Airflow Guidance in Driving

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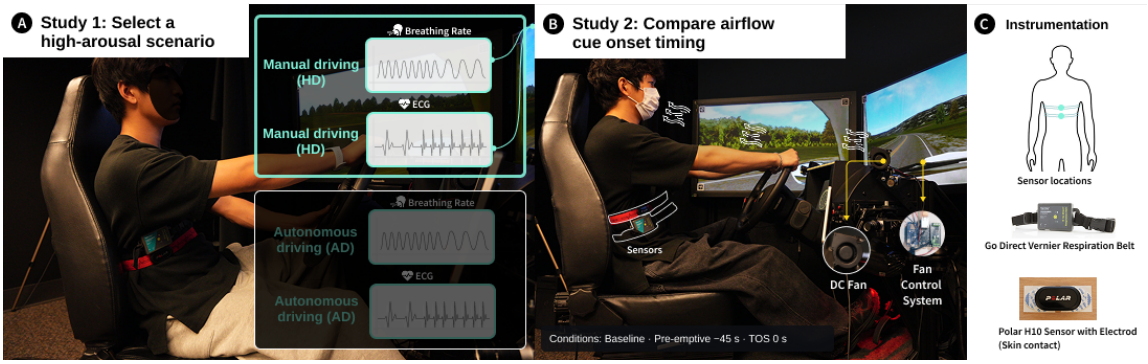


Fig. 1. **Study workflow.** A formative study characterized candidate driving contexts and selected a manual-driving traffic scenario for the main timing evaluation of baseline, TOS, and preemptive airflow guidance.

Just-in-time adaptive intervention (JITAI) frameworks emphasize delivering support when users are both in need and receptive, but leave open how support should be timed around predictable stressors. We studied rhythmic airflow guidance during simulated driving, comparing no guidance, airflow beginning at traffic onset (time-of-stressor; TOS), and airflow beginning 45 seconds before traffic onset (preemptive). A formative study ($N = 10$) selected a manual-driving traffic context; a within-subject study ($N = 24$) evaluated the timing conditions. TOS and preemptive guidance produced similar breathing-rate reductions, but preemptive guidance was associated with a larger RMSSD-related cardiac response and lower perceived mental demand than TOS. Interview data suggested that earlier

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airflow gave participants time to notice and incorporate the cue before demand increased. These findings support treating preemptive delivery as a bundled timing strategy involving earlier onset, pre-exposure, and anticipatory signaling.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Ubiquitous and mobile computing*; *Empirical studies in HCI*.

Additional Key Words and Phrases: breathing guidance, stress regulation, driving simulator, heart rate variability, entrainment, haptics, airflow

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1 Introduction

High-arousal emotional states such as stress and anxiety can substantially shape driver behavior, affecting attention, decision making, braking, and responses to challenging traffic situations [9]. Researchers have therefore explored low-effort peripheral interventions, particularly rhythmic breathing airflow guidance, to support regulation while minimizing interference with the primary driving task [4, 13, 41, 42, 60]. These interventions often rely on respiratory entrainment, which we use here to refer to the systematic slowing of spontaneous breathing in response to an externally imposed slower rhythm. Although such guidance can reduce breathing rate(BR) and support regulation during driving [63], engaging with a new prompt may become more difficult as task demand increases. Multiple Resource Theory similarly predicts greater interference when concurrent tasks compete for overlapping perceptual, cognitive, or response resources[59]. Thus, support may become most relevant precisely when it is also harder to incorporate.

A central challenge for adaptive affective systems is therefore not only determining *when support is needed*, but also identifying*when the user can effectively engage with it.* The Just-in-Time Adaptive Intervention (JITAI) framework similarly emphasizes dynamically changing states of vulnerability, opportunity, and receptivity[37, 39]. Accordingly, "just-in-time" need not imply intervention only after a stressor has begun; rather, it concerns whether, when, and how support should be delivered as user state and context change.

Building on this perspective, we propose the **Anticipatory Need–Receptivity Model (ANRM)** (Fig. 2), which distinguishes predicted upcoming demand, acute regulatory need, and receptivity to intervention. ANRM proposes that these states need not peak at the same moment. For predictable stressors, future demand may become sufficiently foreseeable while users still retain greater capacity to notice and incorporate support. We refer to this interval as a *preemptive opportunity window*. ANRM does not introduce new constructs; it makes one narrower, falsifiable claim that the general framework leaves unspecified: for a predictable stressor, the lag between the moment upcoming demand becomes evidenced (t_{predict}) and the moment receptivity begins to measurably decline (t_{decline}) is greater than zero for at least some class of predictable events. This is a substantive claim, not a restatement, because the null case is equally plausible under JITAI as stated: predictability itself could function as a stressor cue, meaning t_{decline} could coincide with t_{predict}, collapsing the hypothesized window to zero. ANRM would be falsified if future work measuring both quantities directly — for example, using secondary-task reaction time or gaze dispersion as a receptivity proxy, and a controlled predictability manipulation — found no such lag, i.e., $t_{\text{decline}} - t_{\text{predict}} \leq 0$. The present study does not measure t_{predict} and t_{decline} directly; it tests a downstream behavioral consequence consistent with a nonzero lag (Section 7.4), which is why we treat ANRM here as a motivating account rather than as directly confirmed.

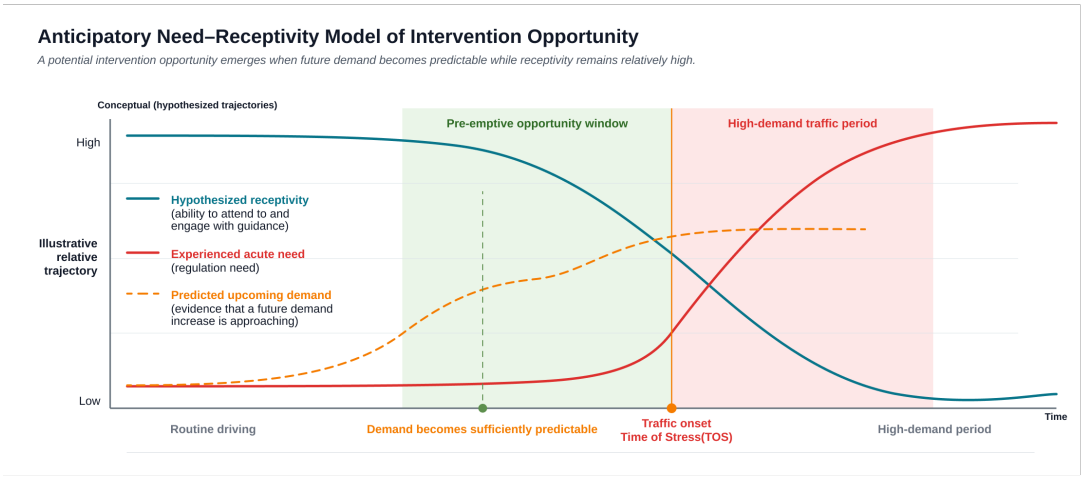


Fig. 2. *Anticipatory Need–Receptivity Model (ANRM).* The trajectories depict hypothesized changes in predicted upcoming demand, acute regulatory need, and receptivity around a predictable high-demand event. ANRM proposes a preemptive opportunity window after future demand becomes sufficiently predictable but before receptivity is substantially constrained. These trajectories are conceptual rather than directly measured; the present study tests one event relative timing contrast rather than an optimal lead time.

In the present study, we examine one event-relative timing implication of ANRM by comparing the same rhythmic airflow guidance initiated either 45 seconds before traffic onset (*preemptive*) or at traffic onset (*time-of-stressor; TOS*). These labels describe the onset timings tested here and do not redefine the broader JITAI framework.

Participants were not instructed to alter their breathing or informed that the airflow was intended to regulate stress, allowing us to examine spontaneous respiratory adaptation with minimal demand characteristics. We hypothesized that both active timing conditions would reduce breathing rate, but that preemptive guidance would be associated with greater RMSSD improvement and lower perceived mental demand than TOS guidance. We tested this across a two-part study: a formative stressor-characterization study ($N = 10$) that identified a manual-driving traffic context, followed by a within-subject study ($N = 24$) comparing no-guidance control, TOS guidance, and preemptive guidance. Because preemptive delivery also introduced additional pre-event airflow exposure and anticipatory information, this comparison should be read as a contrast between two event-relative timing strategies rather than an isolation of onset timing as the sole causal mechanism.

This work addresses two research questions:

- **RQ1:** How are preemptive versus TOS rhythmic airflow guidance associated with respiratory entrainment, respiration-coupled cardiac outcomes, and perceived mental demand during stressful driving?
- **RQ2:** How do participants experience the timing and attentional fit of preemptive versus TOS airflow guidance, and how do these experiences contextualize the quantitative outcomes?

Both active conditions substantially reduced breathing rate, with no reliable difference between them. However, only preemptive guidance produced a reliable RMSSD improvement over no-guidance control, and this improvement also exceeded that observed under TOS guidance, which showed only a trend-level increase; preemptive guidance was additionally associated with lower perceived mental demand than TOS guidance. Qualitative findings further showed that TOS guidance could remain useful in the moment but was more vulnerable to attentional and contextual mismatch

once traffic demand had increased. Together, these findings suggest that comparable respiratory entrainment does not necessarily imply equivalent downstream cardiac or cognitive outcomes, and that the moment of greatest regulatory need may not coincide with the moment of greatest receptivity.

This work makes three contributions. **(1)** We introduce ANRM as a conceptual account of how predicted demand, acute regulatory need, and receptivity may jointly shape intervention timing around predictable high-demand events. **(2)** We provide an event-relative comparison of the same implicit airflow guidance initiated before versus at stressor onset, revealing an entrainment–regulation dissociation across respiratory, cardiac, and mental demand outcomes. **(3)** Our mixed-method findings show that TOS support can remain useful yet become more vulnerable to attentional and contextual mismatch, motivating JIT systems that consider both regulatory need and opportunity for engagement.

2 Related Works

2.1 Emotion, Attentional Resources, and Performance

A driver's emotional state and the availability of attentional resources can significantly affect driving performance, especially in challenging traffic scenarios. Drive theory suggests that arousal levels are associated with an individual's performance [6], a concept further elaborated by the Yerkes-Dodson Law [62], which posits that an optimal level of arousal is needed for peak performance. High arousal often triggers a "fight-or-flight" response via the sympathetic nervous system (SNS), which is frequently characterized by increased heart rate, accelerated breathing, and a reduction in heart rate variability (HRV). This physiological response is often accompanied by emotional experiences or anxiety, which can hinder performance by diverting attention from the primary task and reducing working memory capacity [6, 56]. These observations are supported by two complementary theories, including the attentional control theory (ACT)[19] and the attentional resource theory (ART)[40, 59].

ACT suggests that anxiety impairs the efficiency of the goal-directed attentional system (top-down processing) while increasing the influence of the stimulus-driven system (bottom-up processing)[19]. For in-vehicle affective intervention systems, such effects imply that when a driver most needs to regulate their stress, their ability to follow a new airflow guidance may be reduced. This is further complicated by multiple resource theory, which posits that humans possess a finite pool of cognitive resources[59]. In driving, this creates a potential "attentional bottleneck": stress may impair cognitive processing efficiency through top-down disruption while simultaneously depleting the resources necessary for safe vehicle operation. Introducing a new prompt at demand onset can therefore add a secondary task to an already resource-constrained system, potentially increasing dual-task interference rather than providing immediately usable support [2, 24, 47]. Prior driving research further shows that drivers' receptivity to secondary information varies with momentary driving context, supporting the idea that a JIT system should consider not only need, but also when the driver is available to engage with support. This need–receptivity tension motivates our comparison of preemptive and TOS airflow guidance initiation.

2.2 In-Car Emotion Regulation via Breathing Interventions

Extensive prior works have shown that people's affective state can be modulated through rhythmic entrainment, where physiological rhythms such as breathing and heart rate synchronize with external stimuli [12, 17, 18, 25]. Respiration itself can modulate neural oscillations and synchronization across brain regions involved in sensory, cognitive, and affective processing [1, 3, 29]. Slow-paced breathing has accordingly been associated with improved emotional regulation and reduced perceived stress, although these affective effects are less consistent than its cardiovascular effects [3, 49].

Physiologically, slow breathing increases respiratory–cardiac coupling and vagally mediated HRV, including RMSSD, while also producing modest reductions in heart rate [8, 32, 48, 49].

Building on this mechanism, HCI and human-factors studies have explored how real-time digital interventions can modulate an individual's emotional and physiological state by guiding respiration through multiple interface modalities, including haptic feedback, auditory cues, pneumatic stimulation, and multisensory or airflow-based feedback [4, 13, 20, 34, 42].

Just Breathe [42] demonstrated the effectiveness of seat haptic vibration and audio guidance for slowing drivers' breathing: both modalities reduced breathing rate by approximately 30%, while most participants preferred haptic guidance because it was easier to engage and disengage from the primary driving task. Balters et al. extended this line of work through a closed-circuit driving experiment using a haptic seat, finding that short haptic breathing exercises reduced breathing rate and increased HRV without compromising safety [4]. Similarly, Zepf et al. introduced a closed-loop system that monitored a driver's breathing and delivered subtle acoustic stimuli that entrained breathing rate to 20% below the individual's no-guidance control without impairing driving performance [63]. Beyond audio and generic vibrotactile cues, Choi et al. [13] showed that a personalized pneumatic-tactile cue using a barely perceivable stimulus achieved an Average breathing rate decrease of 24.8% in 80% of their participants, while introducing no extra stress. Together, these studies indicate that minimally obtrusive peripheral guidance can reliably induce rhythmic entrainment in breathing, leading to a calmer driving experience. Inspired by these prior works, we explore delivering breathing guidance using rhythmic airflow pulses, which offer discrete, subtle haptic stimuli that mimic natural cabin air conditioning.

2.3 Anticipatory Timing for Regulation

The literature reviewed above establishes two ingredients of our timing question: peripheral breathing airflow pulses can support respiratory entrainment during driving (Section 2.1), while drivers' capacity to accommodate secondary input varies with momentary task demand. A complementary body of work suggests that regulation-relevant information can become available *before* a demanding event reaches its peak. In driving, cues preceding predictable road hazards elicit anticipatory cardiac, pupillary, and behavioral responses, and advance warning of upcoming congestion can alter subsequent frustration-related driving behavior [26, 28]. Future driver stress can also, in some settings, be predicted ahead of the event [14]. Together, these findings establish that upcoming demand may become actionable before the corresponding high-demand episode begins.

Research outside driving provides converging evidence that regulatory processes can also be initiated in anticipation of a known stressor. Proactive-coping and pre-task regulation studies have shown that slow-breathing or cardiac-biofeedback interventions delivered before stressful medical or performance tasks can influence subsequent anxiety, calmness, and physiological regulation [16, 45, 46]. These studies do not establish that earlier intervention is generally superior, nor do they identify an optimal anticipatory interval. Rather, they demonstrate that pre-event regulation is feasible and that the period preceding a foreseeable stressor can itself be a meaningful intervention target.

To our knowledge, existing works have not explored how the *same* low-effort regulatory airflow guidance behaves when introduced at different points relative to the onset of a predictable high-demand event. Prior in-vehicle breathing systems have demonstrated respiratory guidance during driving [4, 34, 42, 63], whereas anticipatory driving studies have primarily examined prediction, warning, or hazard preparation. As summarized in Table 1, we found no prior study that holds the regulation modality and stressful driving context constant while directly contrasting a breathing-based airflow guidance introduced shortly before versus at the onset of the same predictable stressor. Our study addresses

Table 1. Evidence-to-gap matrix positioning this work relative to prior interruption, anticipation, and breathing-regulation research. ✓ indicates direct coverage, △ indicates partial or indirect coverage, and - indicates that the dimension was not a focus of the work.

Work	Driving	Regulation	Anticipatory Context	Receptivity / Timing	Pre-event Intervention	TOS Intervention	Direct Timing Comparison
Adamczyk & Bailey [2]	–	–	–	✓	–	–	–
Johnson & McKnight [26]	✓	△	✓	–	✓	–	–
Just Breathe [42]	✓	✓	–	–	–	during	–
Semmens et al. [47]	✓	–	△	✓	–	–	–
Schlatter et al. [46]	–	✓	✓	–	✓	–	–
AmbientBreath [34]	✓	✓	–	✓	–	✓	–
Clark et al. [14]	✓	–	✓	–	proposed	–	–
Koch et al. [30]	✓	✓	△	✓	–	△	–
Kerautret et al. [28]	✓	–	✓	△	cue only	–	–
This work	✓	✓	✓	✓	✓	✓	✓

this empirical gap through an event-relative comparison of preemptive and TOS delivery. Because preemptive delivery necessarily also introduces pre-event airflow guidance exposure and anticipatory signaling, this comparison should be understood as a contrast between two timing strategies rather than as an isolation of airflow guidance onset as the sole causal mechanism.

3 Study Overview

We conducted a two-part study to investigate how event-relative airflow guidance onset is associated with regulation-related outcomes during simulated driving. Study 1 was a formative scenario-selection study that characterized responses to the candidate traffic scenario and identified an appropriate manual-driving context. Study 2 then compared no-guidance baseline, TOS, and preemptive airflow breathing guidance within that context. Both studies received institutional review board (IRB) approval.

3.1 Apparatus and Hardware Setup

All experimental trials were conducted using the miniSim driving simulator, a mid-fidelity research platform. To monitor physiological responses, we used a Vernier Go Direct respiration belt [55] worn around the chest to monitor breathing through the expansion force (sampled at 10 Hz, 0.01 N resolution). For cardiac monitoring, we used a Polar H10 heart monitor [43] placed around the lower sternum. Raw electrocardiogram (ECG) data from the Polar H10 sensor (built-in 0.7 - 40 Hz bandpass, 130 Hz sample rate) are collected using the PolarBand2lsl library [51]. Based on feedback from formative studies, we developed custom adapters for the Polar H10 sensors to connect to standard adhesive ECG electrode pads to improve user comfort and to minimize the extra respiratory burden caused by the chest strap.

We designed the intervention system (Fig. 3) to deliver real-time rhythmic breathing airflow guidance triggered by events in the simulation. The miniSim program transmitted UDP packets containing state flags (ON/OFF) over a wired Ethernet network to an Adafruit nRF52840 microcontroller. The microcontroller, fitted with a W5500 Ethernet shield and a TB6612 motor driver, controlled two Mechatronics B7530 DC blower fans. Positioned adjacent to the driver's side air conditioning vent, these fans delivered airflow pulses in a cyclic sine wave pattern at a frequency of 70% of the individual's baseline breathing rate(BR) to simulate calm, natural breathing.

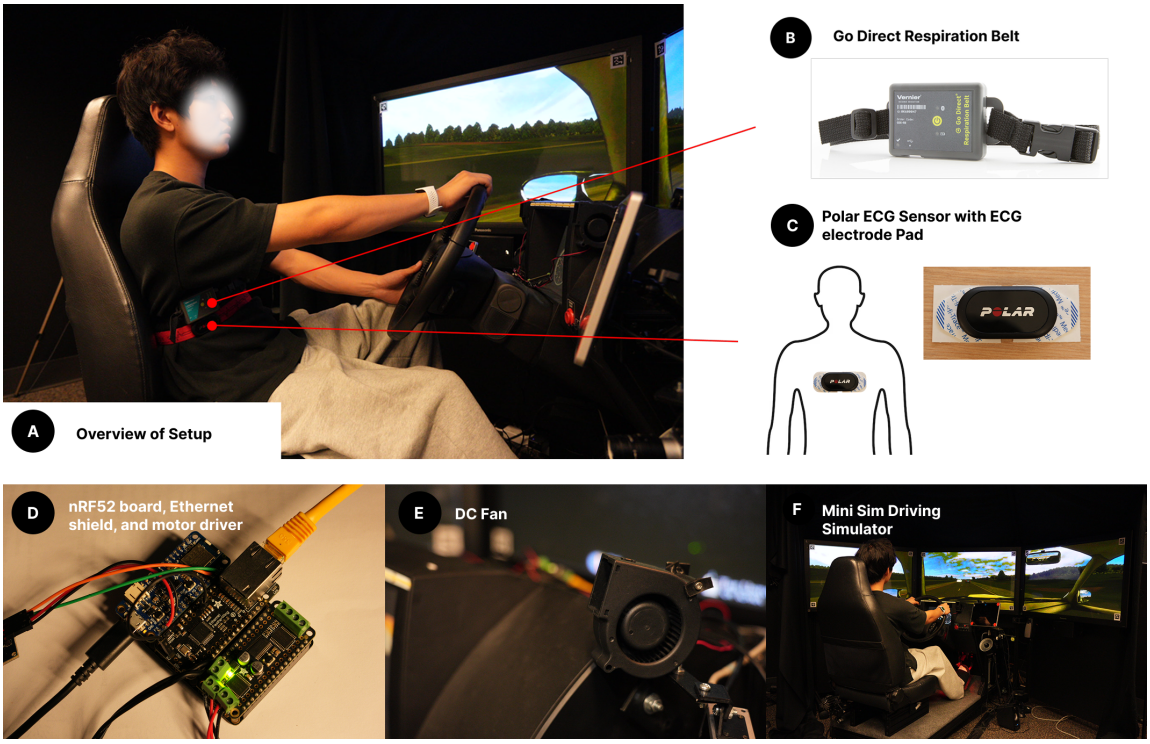


Fig. 3. *The simulated driving study setup. (a) The miniSim™ PC-based driving simulator (b) Vernier Go Direct Respiration Belt (c) Polar H10 Heart Rate Sensor*

4 Study 1: Formative Stressor Characterization and Scenario Selection

To select an appropriate high-arousal driving context for the main timing evaluation in Study 2, we conducted a small formative study ($N = 10$; 4 men, 6 women; $M = 28.5$, $SD = 7.3$) comparing manual (HD) and autonomous (AD) driving under the same traffic scenario constructed from prior work on speed mismatch, cut-in events, merging complexity, and dense traffic [7, 22, 36, 44, 50, 57, 58, 61, 64]. Participants completed both conditions in counterbalanced order while we recorded heart rate (HR), heart rate variability (HRV, RMSSD), breathing rate, and subjective arousal/valence (SAM) and state anxiety (STAI); full procedure is reported in Appendix A.

Manual driving produced a clearer autonomic stress profile than autonomous driving. RMSSD decreased significantly during HD traffic ($p = .017$) but not AD ($p = .885$), with a significant between-mode difference ($p = .049$). HR increased significantly in HD ($p = .023$) but not AD ($p = .795$; between-mode $p = .034$). SAM valence also worsened significantly only in HD ($p = .009$). Breathing rate showed the opposite pattern, increasing significantly in AD but not HD — consistent with AD driving eliciting a qualitatively different, less classically stress-like response in this sample. Full statistical models, effect sizes, and additional measures are reported in Appendix A. Based on this clearer and more consistent stress profile, we selected the manual-driving scenario as the common stress context for the timing evaluation in Study 2.

5 Study 2: Breathing-Intervention Timing Evaluation

Study 2 evaluated one event-relative timing contrast motivated by ANRM: whether the same implicit respiratory airflow guidance produces different downstream outcomes when initiated before versus at the onset of predictable task demand. We compared three within-subject conditions: no-guidance baseline, preemptive guidance, and TOS guidance. Addressing RQ1, we tested three hypotheses, each targeting one of the outcome domains named in that question: **(H1)**, addressing respiratory entrainment, both active timing conditions would reduce breathing rate relative to baseline during the time of interest (TOI), reflecting respiratory adaptation toward the airflow guidance rhythm; **(H2)**, addressing respiration-coupled cardiac outcomes, preemptive guidance would be associated with greater RMSSD improvement than TOS guidance; and **(H3)**, addressing perceived mental demand, preemptive guidance would be associated with lower perceived mental demand than TOS guidance during stressful driving. RQ2 is addressed separately through the qualitative interview analysis reported in Section 5.5.

5.1 Experimental Design

The experiment employed a within-subject repeated-measures design. Each participant completed three driving sessions corresponding to three timing conditions: Baseline, preemptive, and TOS. The order of the three conditions was counterbalanced across participants to reduce potential order and habituation effects.

Each driving session used the stressful driving scenario selected in Study 1 and included two sequential traffic contexts: a 4-minute no-traffic baseline segment followed by a 4-minute with-traffic stress segment. During both segments, participants were instructed to drive at approximately 60–65 mph. The no-traffic segment served as the within-session baseline window for physiological measures, including BR, HR, and HRV. The with-traffic stress segment served as the primary time of interest (TOI) for evaluating physiological and subjective responses under stress.

The no-guidance condition served as control condition, with the participants completing the same driving scenario without airflow breathing guidance. In the preemptive condition, airflow breathing guidance began approximately 45 seconds before the onset of the stressful traffic segment and continued throughout the 4-minute traffic segment. The 45-second lead time was selected as a practical anticipatory interval rather than as an assumed optimal timing. Prior driving research has shown that upcoming stress and hazardous events can become actionable before their onset: future driver stress has been predicted up to approximately one minute ahead, and predictable hazards elicit measurable anticipatory physiological and behavioral responses before the hazardous event occurs [15, 27, 28]. Together with preliminary testing, this evidence motivated a 45-second interval that allowed participants to experience several cycles of the personalized breathing rhythm before traffic onset while keeping the intervention temporally proximal to the upcoming stressor. In the TOS condition, airflow breathing guidance began at traffic onset and continued throughout the 4-minute traffic segment, with an additional 45 seconds after the stress segment to match the total airflow guidance duration of the preemptive condition.

In the active intervention conditions, airflow breathing guidance was delivered from the side of the simulator dashboard and was calibrated to guide participants toward a breathing rate approximately 30% lower than their individual baseline breathing rate. Participants were given a 4-minute rest period between driving sessions.

For the primary physiological analyses, the 4-minute with-traffic TOI was compared with the matched 4-minute no-traffic baseline segment from the same driving session. Percentage change scores were computed for BR, HR, and HRV by comparing the TOI against the corresponding within-session baseline. Thus, intervention onset condition

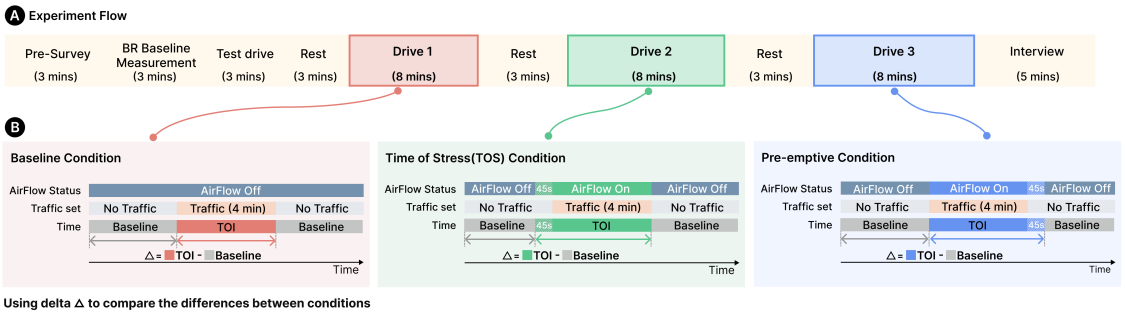


Fig. 4. *Overview of the study design and analysis framework.* **A** shows the experimental procedure, including the pre-survey, breathing-rate baseline measurement, test drive, three experimental drives separated by rest periods, and the semi-structured interview. Each experimental drive included pre-drive SAM and STAI measures, a driving session with or without airflow guidance, and post-drive SAM, STAI, and NASA-TLX measures. **B** illustrates the temporal structure of the baseline, preemptive, and TOS conditions. Changes within each condition were calculated relative to its corresponding baseline period, and these change scores were subsequently compared across conditions to evaluate the effects of intervention onset.

(no-guidance control, preemptive, or TOS) and traffic context (no-traffic vs. with-traffic) were both manipulated within participants.

5.2 Participants

We recruited 24 participants. All participants held a valid driver's license, reported no major stressful, anxiety-provoking, or depressive events within the prior 72 hours, and reported no drug or alcohol use within the prior 48 hours. Sessions lasted approximately 1 hour, and participants received $20 compensation or 1 SONA credit towards Introduction to Psychology Class. We got consent from participants before the study session.

Physiological data were available from all 24 participants. For the primary cardiac analyses, P4 and P17 were excluded for distinct reasons. P4 was excluded on signal-quality grounds because raw ECG/RR inspection identified a pronounced signal disruption and unreliable R-peak detection in the TOS time-of-interest window. P17 did not show comparable raw-signal failure but exceeded a conservative 3×IQR influence threshold for RMSSD percentage change and was therefore treated as an extreme cardiac-derived influence case. Accordingly, the primary HRV and HR analyses included 22 participants. Sensitivity analyses restoring the excluded observations were conducted to evaluate the robustness of the condition effects.

For survey analyses, two participant responses were excluded: one because the response set was incomplete, and one because the participant did not complete the survey measures. This yielded an analytic sample of 22 participants for survey analyses.

For the qualitative analyses, interview data were available from 22 participants. One participant did not complete the full experimental session, and interview data with another participant was unavailable because the recording could no longer be retrieved. These two participants were therefore excluded from the qualitative analysis.

Table 2. Participant inclusion and exclusion by data type.

Data Type	Enrolled	Excluded	Final N	Reason
ECG	24	2	22	Artifact or P17: extreme influence value
Survey	24	2	22	Participants dropped earlier
Respiration	24	0	24	None
Interview	24	2	22	1 incomplete sessions + 1 unavailable recording

5.3 Procedure and Task

After providing informed consent, participants completed a brief screening covering driving experience, prior exposure to breathing-guidance technologies, respiratory conditions, and simulator-sickness history. We then instrumented participants with the Polar H10 ECG sensor[43] and the Vernier Go Direct respiration belt[55].

Participants first sat quietly for 5 minutes while listening to lo-fi music (no talking, no phone use, eyes open) to reduce potential affective carryover from activities outside the laboratory. Breathing baseline was computed as the mean of the final 3 minutes that met a predefined stability criterion (rolling 30-second windows with absolute change < 2 breaths/min and slope < 0.1 breaths/min per minute). Once a stable baseline breathing rate was obtained, the rhythmic airflow pulse rate was individualized to 70% of the participant's baseline breathing rate.

Importantly, **participants were not instructed to alter, synchronize, or otherwise regulate their breathing in response to the airflow**, nor were they informed that the airflow was intended to influence breathing or regulate stress. The rhythmic airflow was therefore introduced without an explicit breathing task, allowing us to examine whether exposure to the slower peripheral rhythm was associated with spontaneous changes in respiration during driving.

Participants then completed a 3–5-minute familiarization drive in the different scenario from the experimental scenario to learn the accelerator, brake, lane keeping, and mirrors. After the familiarization drive, participants rested for 3 minutes and completed pre-drive SAM arousal/valence [10] and STAI [52] measures.

Each participant completed three simulator drives featuring the high-arousal scenario selected in Study 1. Each drive contained a baseline segment (4 minutes at 60–65 mph, no traffic) and a stress segment (4 minutes, dense interacting traffic). The order of the three onset conditions (no-guidance control without airflow guidance, TOS guidance, and preemptive guidance) was counterbalanced across participants. After each drive, participants completed post-drive 9-point SAM, 4-point STAI, and 7-point NASA-TLX [21] measures. After intervention drives, participants also completed a 7-point experience scale capturing noticeability, timing fit, helpfulness, distraction, comfort, naturalness, and timing preference. After completing all three drives, participants completed a semi-structured interview probing perceived timing fit, efficacy, distraction, comfort, and naturalness.

The preemptive condition was intentionally designed to leverage a period in which an upcoming traffic stressor is foreseeable but driving demand has not yet peaked. Rather than treating early airflow guidance delivery only as a warning, the design rationale was to give drivers time to notice the approaching high-demand event, become familiar with the peripheral airflow rhythm, and gradually incorporate the rhythm into their breathing before entering dense traffic. In this sense, the pre-event interval was conceived as an opportunity for anticipatory preparation and for proceduralizing engagement with the breathing airflow guidance, rather than requiring drivers to begin adapting to a new rhythm while simultaneously managing high traffic demand.

This timing strategy is plausible in real-world driving contexts in which upcoming demand can be inferred before it is encountered, for example from navigation displays indicating congestion, an approaching merge, a construction

zone, or a predicted slowdown. Such information could enable an in-vehicle system to identify a pre-event opportunity window and introduce low-effort respiratory guidance while drivers still have sufficient attentional capacity to notice and adapt to it.

5.4 Quantitative Analysis

5.4.1 Physiological Measures and Signal Processing. Physiological signals in Study 2 were processed using the multilevel modeling pipeline described in Section 5.4.2. For Study 2-specific analyses, HR, BR, and HRV (RMSSD) were computed over continuous, task-aligned segments corresponding to the no-traffic baseline driving period and the TOI stress-driving period, each designed to last 4 minutes.

Due to natural variability in traffic onset and driving dynamics, the effective duration of analyzable data within these segments varied slightly across participants and conditions. To ensure stable HRV estimation, only segments containing at least 3 minutes of continuous, artifact-free data were included in the primary statistical analyses. These continuous segments were used exclusively for hypothesis testing.

ECG quality control and influence screening. Raw ECG and RR-interval series were visually and quantitatively inspected before the Study 2 cardiac analyses. P4 was excluded on signal-quality grounds. In P4's TOS time-of-interest window, a pronounced raw ECG disruption produced nonphysiological RR intervals (7,288 ms and 3,835 ms) and unreliable R-peak detection. Although implausible RR intervals were removed during automated screening, the disruption also affected adjacent retained intervals, making RMSSD estimation for this window unreliable. This trial therefore failed the ECG quality-control criteria.

We separately examined derived cardiac percentage-change values using a conservative 3×IQR influence diagnostic. P17 exceeded this threshold for RMSSD percentage change but did not show comparable evidence of raw ECG artifact or unreliable R-peak detection. We therefore treated P17 as an extreme cardiac-derived influence case rather than as a signal-quality failure.

For the primary cardiac analyses, both P4 and P17 were excluded, but for different reasons: P4 on signal-quality grounds and P17 on influence grounds. To maintain a common participant set across conditions and cardiac outcomes, the primary HRV and HR models were fit to the remaining 22 participants. Because P4's signal-quality failure was localized to the TOS trial, we additionally examined alternative observation-level inclusion rules in sensitivity analyses. We also repeated the cardiac analyses with P17 restored to evaluate whether the primary condition effects depended on this influential case.

5.4.2 Statistical Analysis. In Study 2, we used linear mixed-effect models to evaluate associations between breathing-guidance timing conditions and physiological and subjective responses for repeated observations within participants. For the physiological outcomes (HRV, HR, and BR), we computed within-session percentage-change scores relative to the matched baseline period. Models included intervention condition and trial order as fixed effects and a participant-specific random intercept. Trial order was retained because its inclusion significantly improved model fit ($p < .05$).

$$Y_{ij} = \beta_0 + \beta_1 \text{Condition}_{ij} + \beta_2 \text{TrialOrder}_{ij} + u_{0j} + \epsilon_{ij} \tag{1}$$

where Y_{ij} represents the percentage change score for participant j in trial i, Condition_{ij} represents the intervention condition, TrialOrder_{ij} represents the presentation order of the condition, u_{0j} is the participant-specific random intercept, and ϵ_{ij} is the residual error.

Multilevel Modeling Assumption Checks. We evaluated the assumptions of the multilevel models for BR, HR, and HRV using residual diagnostics. Q-Q plots indicated that the residuals were generally consistent with approximate normality, although minor deviations were observed in the distribution tails. Shapiro-Wilk tests did not reject the normality assumption for BR ($W = 0.972$, $p = .198$), HR ($W = 0.982$, $p = .568$), or HRV ($W = 0.970$, $p = .197$). Residuals-versus-fitted plots did not show clear systematic trends, suggesting no severe heteroscedasticity. We also inspected Q-Q plots of the participant-level random intercepts and checked for singular fits. None of the final physiological models showed singular fit, supporting the use of the random-intercept model structure.

All mixed-effects models were fit in R using the `lme4` [5] and `lmerTest` [31] packages. Estimated marginal means and post-hoc pairwise contrasts were computed using `emmeans` [35].

Primary analyses. The primary analyses tested the effect of event-relative airflow guidance-onset condition on HRV, HR, and BR percentage change. Baseline was treated as the reference condition, and TOS and preemptive guidance were compared against this reference. We additionally tested whether condition effects depended on presentation order by comparing models with and without the Condition × TrialOrder interaction. Because the interaction terms did not significantly improve model fit, they were not retained in the final physiological models. Pairwise post-hoc comparisons between conditions were conducted using estimated marginal means with Benjamini-Hochberg correction for multiple comparisons. Standardized effect sizes for pairwise contrasts were estimated using the residual standard deviation from the corresponding mixed-effects model.

Respiration-adjusted HRV sensitivity analysis Because paced breathing can influence RMSSD through respiratory sinus arrhythmia, we conducted a sensitivity analysis to examine whether condition-related differences in RMSSD remained after accounting for concurrent breathing-rate change. We refit the HRV mixed-effects model using the same complete-case observations and added breathing-rate percentage change as a time-matched covariate, while retaining onset condition, trial order, and participant random intercept. We additionally repeated this analysis using only the two active onset conditions (TOS and preemptive) to directly test whether their RMSSD difference persisted after adjustment for respiratory slowing. Condition-specific associations between breathing-rate change and RMSSD change were examined descriptively using Pearson and Spearman correlations.

Subjective outcomes. SAM arousal, SAM valence, and the nine-item STAI-derived state-anxiety composite were analyzed using the same mixed-effects framework as the physiological outcomes. Within-participant pre-post percentage-change scores were treated as approximately continuous outcomes, with onset condition and trial order included as fixed effects and participant as a random intercept. Although the underlying SAM responses and STAI items were collected using ordinal response formats, these mixed-effects models served as the primary analyses because our inferential question concerned whether the magnitude of within-participant change differed across onset conditions.

To complement these models, we also examined the raw ordinal pre-post responses using paired Wilcoxon signed-rank tests within each condition, with Benjamini-Hochberg correction for multiple comparisons. These analyses were used to characterize within-condition affective changes and were not treated as direct non-parametric tests of the between-condition timing effect.

NASA-TLX outcomes were analyzed separately using linear mixed-effects models with onset condition and trial order as fixed effects and participant as a random intercept. Because our primary workload hypothesis concerned perceived mental demand, the Mental Demand subscale was the focal NASA-TLX outcome, while the remaining subscales were treated as secondary outcomes. Because NASA-TLX subscales were collected using 7-point ordinal response scales, we additionally conducted Friedman tests and paired Wilcoxon signed-rank tests as non-parametric sensitivity analyses of

the condition comparisons. Feedback ratings were analyzed only for the two active intervention conditions because these items were not administered in the no-guidance control condition.

5.5 Qualitative Analysis: Thematic Analysis

We conducted semi-structured interviews to understand how participants experienced the timing and attentional fit of airflow breathing guidance during stressful driving. Interview data were available from 22 Study 2 participants. The interviews focused on perceived timing fit, distraction, ease of engaging with the airflow rhythm, perceived calmness, and moments when participants chose to attend to or ignore the guidance.

Three researchers independently reviewed the cleaned interview responses using an inductive, descriptive coding approach informed by thematic analysis and qualitative content analysis [11, 23]. The unit of analysis was the interview excerpt rather than the participant. A participant could therefore contribute multiple excerpts across conditions and topics. For each excerpt, we recorded the participant ID, the timing condition being discussed, and the driving context when identifiable, such as lower-demand driving, traffic onset, or higher-demand maneuvers. Researchers identified codes related to intervention timing, attention allocation, distraction, adaptation to the airflow rhythm, perceived usefulness, comfort, and breathing engagement.

After independent coding, the researchers met to compare candidate codes and supporting excerpts. Similar codes were consolidated into broader experiential themes, and disagreements were resolved through discussion and by returning to the surrounding transcript context. Excerpts could receive more than one code when they expressed multiple experiential dimensions, such as both timing mismatch and distraction. Consequently, theme frequencies reported below are not mutually exclusive. Because the unit of analysis was the excerpt, these frequencies characterize recurring patterns in the interview corpus and should not be interpreted as the proportion of participants endorsing a particular view.

6 Results from Study 2

6.1 Reduced breathing rate and more favorable cardiac responses under preemptive guidance

Before cardiac inferential modeling, we screened cardiac-derived percentage-change values using a conservative 3×IQR rule. P4 showed a clear RR-interval artifact in the TOS analysis window, and P17 produced an influential HRV percentage-change value under the same screening rule. Therefore, the primary HRV and HR analyses used the same cardiac-analysis sample excluding P4 and P17 ($N = 22$ participants, 66 observations). BR analyses retained all available physiological participants because these participants were not breathing-rate outliers ($N = 24$ participants, 72 observations).

BR. The ICC for the primary BR model is 0.09. After accounting for trial order, the linear mixed-effects model showed a significant effect of condition on breathing-rate percentage change (Fig. 5). Relative to the no-guidance control condition, TOS guidance was associated with significantly lower BR percentage change ($\beta = -24.73$, $SE = 4.83$, $p < .001$, $d = -1.48$), and preemptive guidance was also associated with significantly lower BR percentage change ($\beta = -21.22$, $SE = 4.88$, $p < .001$, $d = -1.27$). BH-corrected post-hoc contrasts confirmed that BR percentage change was higher in no-guidance control than in TOS guidance ($\beta = 24.73$, $SE = 4.99$, $p_{\mathrm{BH}} < .001$, $d = 1.48$) and higher in no-guidance control than in preemptive guidance ($\beta = 21.22$, $SE = 5.04$, $p_{\mathrm{BH}} < .001$, $d = 1.27$). TOS and preemptive guidance did not significantly differ from each other ($\beta = -3.52$, $SE = 5.06$, $p_{\mathrm{BH}} = .490$, $d = -0.21$). Trial order was not significant ($\beta = 3.97$, $SE = 2.45$, $p = .113$).

Table 3. Primary and sensitivity analyses of the RMSSD timing effect. The primary HRV analysis excluded P4 and P17 based on cardiac data-quality/influence screening. BR analyses retained all available physiological participants.

Test	Result	Interpretation
BR: TOS vs. preemptive	$p_{BH} = .490$, $d = -0.21$	No reliable difference in breathing-rate reduction between the two active timing conditions.
Primary HRV: P4 and P17 excluded	$\beta = 16.77$, $SE = 6.01$, $p_{BH} = .011$, $d = 0.88$	preemptive guidance produced greater RMSSD percentage change than TOS guidance in the primary cardiac-analysis sample.
HRV with P4 and P17 retained	$\beta = 10.06$, $SE = 8.23$, $p_{BH} = .227$, $d = 0.37$	The preemptive–TOS difference remained directionally consistent but was no longer statistically reliable when both influential observations were retained.
Observation-level 3×IQR sensitivity	$\beta = 15.89$, $SE = 5.72$, $p_{BH} = .012$, $d = 0.85$	Removing only HRV observations exceeding the 3×IQR threshold yielded the same directional pattern and inference.
Log-RMSSD sensitivity: P4 and P17 excluded	$\beta = 0.130$, $SE = 0.048$, $p_{BH} = .014$, $d = 0.85$	The preemptive–TOS difference remained reliable when modeling log-transformed RMSSD change rather than percentage change.
All-condition, BR-adjusted HRV sensitivity	$\beta = 17.50$, $SE = 6.00$, $p_{BH} = .008$, $d = 0.94$	The preemptive advantage over TOS guidance remained statistically reliable after adjusting for concurrent breathing-rate change.
Intervention-only, BR-adjusted HRV sensitivity	$\beta = 16.12$, $SE = 5.91$, $p = .011$, $d = 0.91$	Among active conditions only, the preemptive advantage remained statistically reliable after adjustment for concurrent breathing-rate change.

HRV. The ICC for the primary HRV model was 0.44. After accounting for trial order, preemptive guidance was associated with significantly greater RMSSD percentage change than no-guidance control ($\beta = 27.82$, $SE = 5.83$, $p < .001$, $d = 1.46$). TOS guidance showed a smaller, trend-level increase relative to no-guidance control ($\beta = 11.05$, $SE = 5.73$, $p = .060$, $d = 0.58$). BH-corrected pairwise contrasts confirmed that RMSSD change was greater under preemptive guidance than under no-guidance control ($\beta = 27.82$, $SE = 6.03$, $p_{BH} < .001$, $d = 1.46$) and greater under preemptive guidance than under TOS guidance ($\beta = 16.77$, $SE = 6.01$, $p_{BH} = .011$, $d = 0.88$). The no-guidance control versus TOS contrast did not reach significance after correction ($\beta = 11.05$, $SE = 5.94$, $p_{BH} = .069$, $d = 0.58$). Trial order was not significant ($\beta = 1.28$, $SE = 2.92$, $p = .664$).

To further evaluate whether this preemptive–TOS RMSSD difference depended on the specific exclusion threshold used, we re-estimated the contrast using Huber robust regression on the full cardiac sample (P4 and P17 retained), which continuously downweights influential observations rather than removing them. The contrast remained statistically reliable ($\Delta = 10.3$, 95% CI [1.62, 19.0], p = .020), and inspection of the fitted robust weights confirmed that P4's trial and P17's baseline trial received substantially reduced weight, independently corroborating the 3×IQR-based influence screening reported above. Full bootstrap and robust-regression sensitivity details are reported in Appendix C.3.

HR. The ICC for the primary HR model was 0.18. Preemptive guidance was associated with significantly lower HR percentage change than no-guidance control ($\beta = -2.56$, $SE = 0.90$, $p = .007$, $d = -0.87$), whereas TOS guidance did

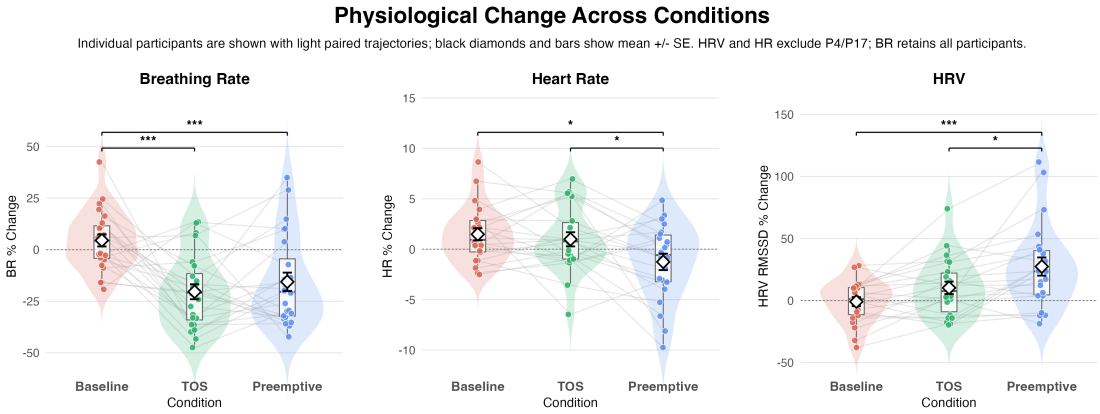


Fig. 5. *Physiological percentage change by condition.* Lines connect individual participants across conditions; black points and error bars show condition means and standard errors. Both TOS and preemptive guidance reduced breathing-rate percentage change relative to baseline, while preemptive guidance showed the clearest RMSSD improvement.

not significantly differ from no-guidance control ($\beta = -0.48$, $SE = 0.88$, $p = .592$, $d = -0.16$). BH-corrected contrasts showed lower HR percentage change in preemptive guidance than no-guidance control ($\beta = 2.56$, $SE = 0.93$, $p_{\text{BH}} = .025$, $d = 0.87$) and lower HR percentage change in preemptive guidance than TOS guidance ($\beta = 2.08$, $SE = 0.92$, $p_{\text{BH}} = .044$, $d = 0.71$). The no-guidance control versus TOS contrast was not significant ($\beta = 0.48$, $SE = 0.91$, $p_{\text{BH}} = .605$, $d = 0.16$). Trial order was not significant ($\beta = -0.49$, $SE = 0.45$, $p = .282$).

Respiration-adjusted HRV sensitivity analysis. Using the primary cardiac sample excluding P4 and P17, we re-estimated the RMSSD model with concurrent breathing-rate percentage change as a mean-centered covariate. In the model including all three conditions, the adjusted preemptive–TOS contrast remained statistically reliable after BH correction ($\beta = 17.50$, $SE = 6.00$, $p_{\text{BH}} = .008$, $d = 0.94$). Preemptive guidance also remained higher than no-guidance control after respiratory adjustment ($\beta = 22.92$, $SE = 6.99$, $p_{\text{BH}} = .006$, $d = 1.23$), whereas TOS guidance did not differ from no-guidance control ($\beta = 5.42$, $SE = 7.19$, $p_{\text{BH}} = .454$, $d = 0.29$). The breathing-rate covariate itself was not a significant predictor of RMSSD change ($\beta = -0.22$, $SE = 0.15$, $p = .151$), and adding it did not significantly improve model fit, $\chi^2(1) = 2.09$, $p = .149$.

In an intervention-only sensitivity model, the preemptive advantage over TOS guidance likewise remained statistically reliable after adjustment for concurrent breathing-rate change ($\beta = 16.12$, $SE = 5.91$, $p = .011$, $d = 0.91$). These sensitivity analyses suggest that the preemptive RMSSD advantage was not fully explained by concurrent breathing-rate slowing, although they do not establish respiration-independent cardiac effects.

6.1.1 Preemptive reduced mental demand without broader affect differences. **NASA-TLX.** The ICC of the null model for overall workload was 0.68, indicating substantial between-participant variability. We did not observe a significant effect of timing condition on perceived overall workload ($F(2, 44.00) = 1.48$, $p = .239$). Pairwise comparisons also showed no reliable differences between no-guidance control and TOS ($\beta = -0.11$, $SE = 0.15$, $p_{\text{BH}} = .486$, $d = -0.22$), no-guidance control and preemptive feedback ($\beta = 0.15$, $SE = 0.16$, $p_{\text{BH}} = .486$, $d = 0.30$), or TOS and preemptive feedback ($\beta = 0.26$, $SE = 0.15$, $p_{\text{BH}} = .313$, $d = 0.52$).

	HRV_Perc					HR_Perc					BR_Perc				
Fixed Effects	*Estimates*	*SE*	*Statistic*	*p*	*df*	*Estimates*	*SE*	*Statistic*	*p*	*df*	*Estimates*	*SE*	*Statistic*	*p*	*df*
(Intercept)	-3.27	7.68	-0.43	0.671	60.00	2.39	1.09	2.21	**0.031**	60.00	-3.10	5.92	-0.52	0.602	66.00
Condition [TOS]	11.05	5.73	1.93	0.059	60.00	-0.48	0.88	-0.54	0.591	60.00	-24.73	4.83	-5.12	**<0.001**	66.00
Condition [preemptive]	27.82	5.83	4.78	**<0.001**	60.00	-2.56	0.90	-2.85	**0.006**	60.00	-21.22	4.88	-4.35	**<0.001**	66.00
Condition Order	1.28	2.92	0.44	0.663	60.00	-0.49	0.45	-1.09	0.280	60.00	3.97	2.45	1.62	0.111	66.00
Random Effects															
σ^2	360.88					8.54					279.71				
τ_{00}	284.54 $_{PID}$					1.93 $_{PID}$					28.97 $_{PID}$				
ICC	0.44					0.18					0.09				
N	22 $_{PID}$					22 $_{PID}$					24 $_{PID}$				
Observations	66					66					72				

Fig. 6. *Linear mixed-effects model summary.* Estimates represent percentage-point differences in HRV, HR, and BR relative to no-guidance control after controlling for condition order, with participant included as a random intercept. Bold values indicate statistically significant effects at $p < .05$.

However, subscale analyses showed significantly lower Mental Demand in the preemptive condition than in No-guidance control ($\beta = 0.68$, $SE = 0.29$, $p_{\mathrm{BH}} = .037$, $d = 0.73$) and TOS ($\beta = 0.96$, $SE = 0.29$, $p_{\mathrm{BH}} = .006$, $d = 1.02$). No-guidance control and TOS did not differ significantly ($\beta = -0.27$, $SE = 0.29$, $p_{\mathrm{BH}} = .357$, $d = -0.29$). No other NASA-TLX subscale showed significant pairwise differences after correction.

Because NASA-TLX subscales were measured on 7-point ordinal scales, we also conducted non-parametric sensitivity analyses. The Friedman test for Mental Demand was significant after BH correction across NASA-TLX outcomes ($\chi^2(2) = 9.94$, $p = .007$, $p_{\mathrm{BH}} = .049$). Paired Wilcoxon tests showed lower Mental Demand in the preemptive condition than no-guidance control ($V = 75.5$, $p_{\mathrm{BH}} = .048$, $r = .46$) and TOS ($V = 153$, $p_{\mathrm{BH}} = .007$, $r = .65$), using within-outcome BH correction. No other NASA-TLX subscale showed significant pairwise differences after correction.

Taken together, timing condition did not reliably change overall workload, but preemptive airflow feedback specifically reduced perceived mental demand.

SAM and STAI. We analyzed percentage-change scores for SAM arousal, SAM valence, and STAI using linear mixed-effects models with Condition and Trial Order as fixed effects and Participant as a random intercept, using no-guidance control as the reference condition. Relative to baseline, TOS did not significantly affect SAM arousal ($\beta = 7.12$, $SE = 33.49$, $p = .833$, $d = 0.06$), SAM valence ($\beta = -8.00$, $SE = 34.90$, $p = .820$, $d = -0.07$), or STAI ($\beta = 4.28$, $SE = 8.20$, $p = .604$, $d = 0.16$). Likewise, preemptive guidance did not significantly differ from no-guidance control for SAM arousal ($\beta = -36.46$, $SE = 33.70$, $p = .285$, $d = -0.33$), SAM valence ($\beta = -42.96$, $SE = 35.12$, $p = .228$, $d = -0.37$), or STAI ($\beta = 1.40$, $SE = 8.27$, $p = .866$, $d = 0.05$). Trial Order was also not significant for SAM arousal ($\beta = -15.42$, $SE = 16.87$, $p = .365$), SAM valence ($\beta = -4.96$, $SE = 17.57$, $p = .779$), or STAI ($\beta = -4.28$, $SE = 4.14$, $p = .306$). BH-corrected pairwise contrasts showed no reliable between-condition differences for SAM arousal (all $p_{\mathrm{BH}} \geq .453$), SAM valence (all $p_{\mathrm{BH}} \geq .511$), or STAI (all $p_{\mathrm{BH}} = .871$).

6.1.2 Summary of Timing Effects. Taken together, the results suggest that onset-condition differences were consistent with the possibility that event-relative airflow guidance initiation influenced how respiratory entrainment was associated with downstream outcomes. Both active conditions slowed breathing, supporting **H1**: TOS and preemptive guidance did not significantly differ in the magnitude of breathing-rate reduction. Partially consistent with **H2**, preemptive

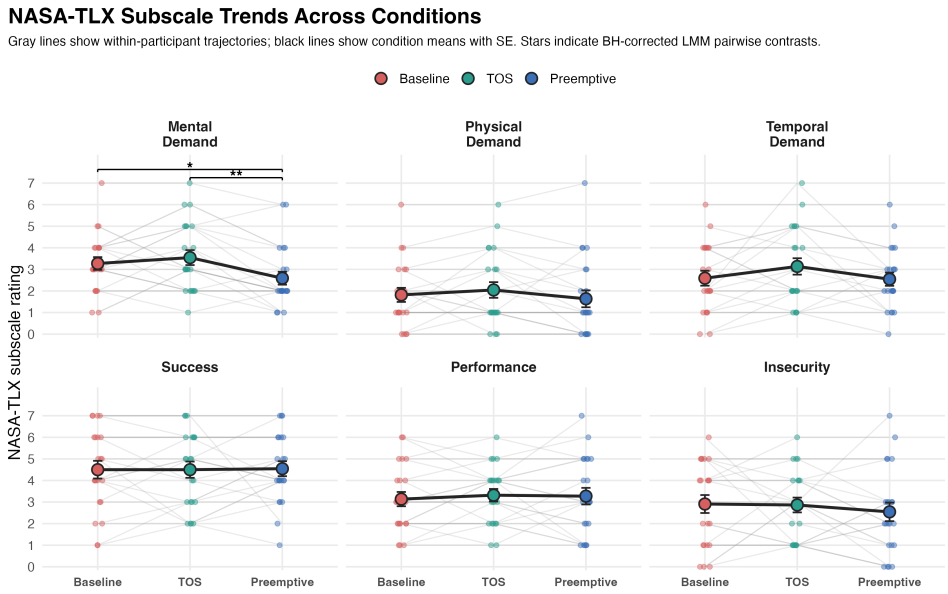


Fig. 7. *NASA-TLX subscale trends across conditions.* Gray lines show within-participant trajectories; black points show condition means with standard errors. Stars indicate Benjamini-Hochberg-corrected pairwise contrasts. Preemptive guidance was associated with lower mental demand than no-guidance control and time-of-stressor (TOS), while other subscales showed less consistent differences.

guidance produced a significant RMSSD improvement over both no-guidance control and TOS guidance. TOS guidance showed only a trend-level RMSSD increase relative to no-guidance control that did not survive correction, so we cannot conclude that TOS guidance reliably improved HRV on its own; rather, preemptive guidance was the only condition that produced a robust RMSSD benefit relative to baseline. Consistent with **H3**, preemptive guidance reduced perceived mental demand relative to both no-guidance control and TOS guidance, although this specificity did not extend to overall NASA-TLX workload.

6.2 Qualitative Results

Across 204 coded interview excerpts, participants did not evaluate the airflow guidance solely in terms of whether it felt calming. Instead, they repeatedly interpreted it through the lens of timing and contextual fit: whether the guidance arrived early enough to be useful, whether it supported regulation in the moment, and whether it fit the attentional demands of the road.

6.2.1 Preparation and Anticipation: Why Preemptive Felt More Supportive. A first pattern was that participants often described preemptive guidance as supportive because it created a preparation window before the demanding driving moment. Across the coded excerpts, *Timing experienced as beneficial* was the most prevalent theme overall (35 excerpts, 17.2%) and the dominant theme within preemptive-focused excerpts (31 of 77 excerpts, 40.3%).

The participants' descriptions suggest that the value of preemptive timing was not simply that it encouraged breathing, but that it did so early enough to be incorporated into driving preparation. As one participant explained, the preemptive airflow guidance "gives me some time to ... get used to it" (P19). Another described preemptive guidance as

Table 4. Thematic evidence for participants' perceptions of preemptive and TOS airflow guidance.

Finding	Evidence	Illustrative excerpt
Preemptive supported anticipatory preparation	In preemptive-focused excerpts, *Timing experienced as beneficial* was the dominant theme (31/77, 40.3%).	"The preemptive one . . . gives me some time to . . . get used to it." (P19)
TOS guidance sometimes supported in-the-moment regulation	Within TOS-focused excerpts, *Stress regulation improved* appeared in 7/37 excerpts (18.9%).	"The air helped me focus on my breathing . . . I was a lot more patient." (P01)
TOS guidance was more often experienced as mistimed	Within TOS-focused excerpts, *Timing experienced as mismatched* was the most frequent theme (13/37, 35.1%).	"The breathing intervention didn't seem well timed . . . it felt unnatural." (P15)
Perceived usefulness depended on context	*Contextual influence* appeared in 19/204 excerpts overall and was especially common in mixed/trade-off excerpts (13/39, 33.3%).	"If the road condition is okay, I could follow it . . . but if there's too many things going on, I don't think I could pay enough attention." (P14)

giving them "enough notice" (P15). These accounts suggest that earlier airflow was often interpreted as an anticipatory airflow guidance that allowed participants to settle into the upcoming traffic segment, rather than as an additional demand competing for attention.

6.2.2 TOS Guidance as Effective but Often Mistimed. A second pattern was that TOS guidance was discussed in more ambivalent terms. On the one hand, participants sometimes described it as helpful when support was needed in the moment. On the other hand, they also described it as more likely to feel poorly timed, abrupt, or distracting once driving demands were already high. This duality appeared clearly in the coded excerpts: within TOS-focused excerpts, *Timing experienced as mismatched* was the most frequent theme (13 of 37 excerpts, 35.1%), followed by *Stress regulation improved* (7 of 37 excerpts, 18.9%).

The participants' own language illustrates this contrast. One participant said that the airflow "...helped me focus on my breathing" and made them feel "a lot more patient" while driving (P01). Yet another described the TOS airflow guidance as something that "didn't seem well timed" and "felt unnatural" (P15). Together, these excerpts suggest that TOS guidance could be helpful in the moment, but was also vulnerable to being experienced as mistimed or effortful.

6.2.3 Context-Dependent Effects. A third pattern was that usefulness and distraction were context-dependent rather than fixed properties of the intervention itself. *Contextual influence* appeared in 19 excerpts overall, and it was especially prominent in the mixed / trade-off comparison excerpts (13 of 39, 33.3%). This suggests that participants did not describe airflow guidance as uniformly good or uniformly distracting; instead, they evaluated it relative to road conditions, attentional demands, and maneuver timing.

Again, the raw transcripts make this pattern clear. Participant 12 said, "If there are things to distract me, then I was having a hard time following the breathing," but added that when traffic remained within expectation, they were still able to follow it. Participant 14 similarly reported that "if the road condition is okay, I could follow it," but "if there's too many things going on, I don't think I could pay enough attention to the breathing guidance." These excerpts indicate that the same airflow guidance could be perceived as supportive in lower-demand moments and harder to use in more complex traffic situations.

7 Discussion

This study compared two ways of timing the same breathing-guidance airflow guidance: introducing it before a stressful driving episode began (preemptive guidance), versus introducing it once the episode had already started (TOS guidance).

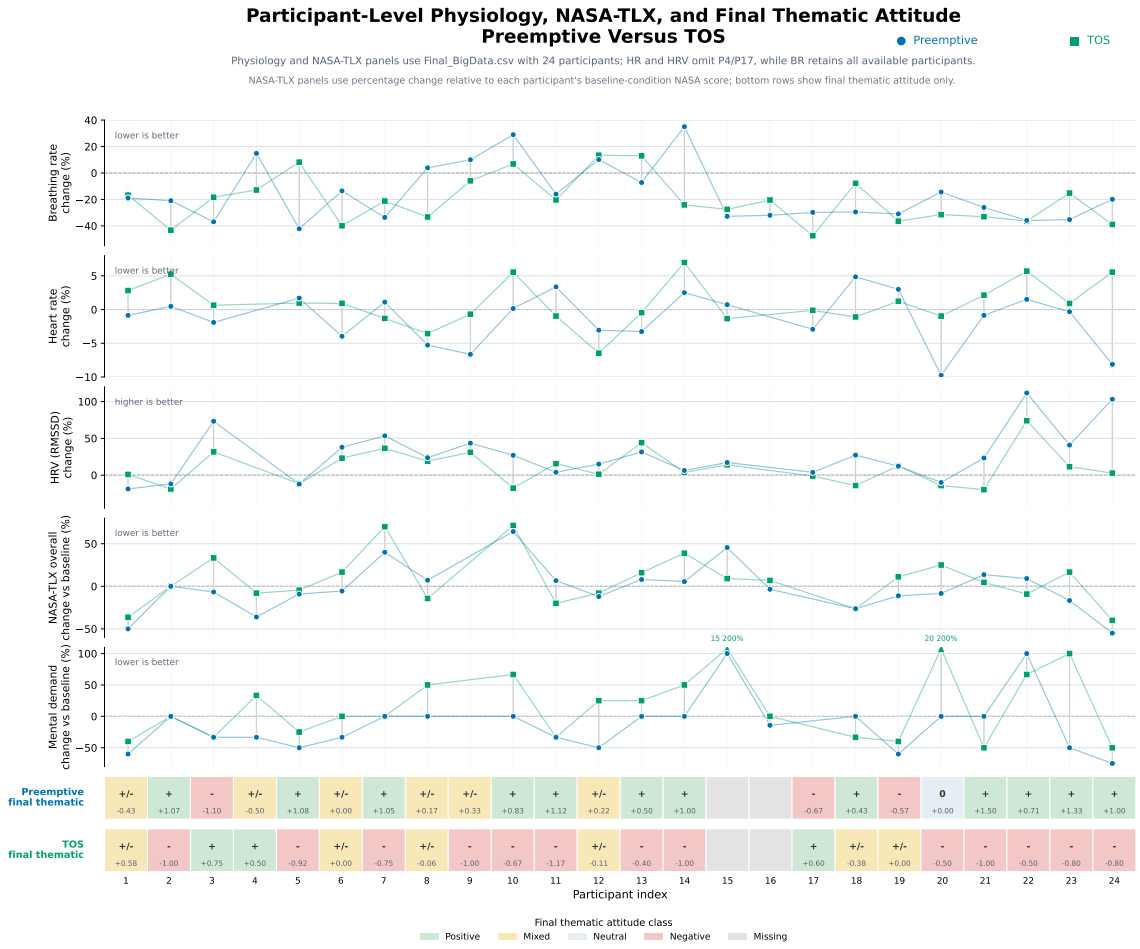


Fig. 8. **Participant-level multimodal patterns for preemptive versus TOS guidance.** Upper panels show participant-level changes in BR, HR, HRV, NASA-TLX overall workload, and mental demand. Physiology values are within-condition baseline-to-traffic percentage changes; NASA-TLX values are percentage changes relative to each participant's baseline-condition score. Red circles indicate preemptive trials and green squares indicate TOS trials. P4 and P17 were excluded from HR/HRV summaries because of signal-quality outliers; P16 and P17 are marked as missing for qualitative data. Lower rows summarize participants' thematic attitudes toward the two timing conditions.

The central finding is not simply that preemptive guidance outperformed TOS guidance overall. Rather, both conditions slowed breathing by a similar amount, yet only preemptive guidance was associated with a reliable downstream improvement in heart-rate variability and perceived mental effort; TOS guidance's own RMSSD change relative to baseline remained at trend level. In other words, the airflow guidance can elicit respiratory adaptation without being introduced at a time that produces the best downstream effects. We interpret this finding through the Anticipatory Need-Receptivity Model (ANRM), introduced below, which separates two questions that are often treated as one: *when does a user start needing support*, and *when is a user still able to make good use of it.*

7.1 Entrainment–Regulation Dissociation: Similar Breathing Response, Different Downstream Outcomes

This distinction matters for designing breathing-based interventions. Prior paced-breathing research has similarly found that breathing, heart-rate, and subjective responses can move independently of one another [33, 53, 54]. Because TOS and preemptive guidance did not reliably differ in how much they slowed breathing, a simple explanation along the lines of "more breathing change means better outcomes" cannot account for our results. Moreover, the RMSSD advantage of preemptive guidance remained reliable even after we statistically adjusted for how much breathing rate had changed. This does not prove that the cardiac benefit is entirely independent of breathing, but it does support a broader point: whether someone's breathing adapted to the airflow guidance does not fully explain how well the intervention worked. This reframes the key design question. It is not only whether users can follow a prompt, but whether the intervention is introduced at a moment that lets that response translate into real benefit. The qualitative results, discussed next, help explain why these two questions can be pulled apart.

7.2 TOS Guidance: High Need, Reduced Receptivity

The qualitative findings help explain why the breathing-rate reductions observed in both conditions did not translate into equivalent downstream outcomes. TOS guidance was not uniformly ineffective: some participants described it as immediately helpful for focusing on their breathing and calming down once traffic became stressful. But TOS guidance was also more often described as mistimed, abrupt, or effortful to follow once traffic demands had already increased. This split was invisible in the physiological data alone: the group-level RMSSD result did not, by itself, reveal these diverging participant experiences (Section 6.1).

This interpretation is consistent with prior work showing that the cost of secondary interaction depends strongly on when it is introduced. Interruptions delivered during high-workload or structurally unfavorable moments produce greater disruption, whereas workload-sensitive timing can identify more opportune moments for interaction [2, 24]. Similar effects have been observed in driving, where receptivity to non-driving information and in-vehicle well-being interventions varies with momentary road context and task demand [30, 47]. Guided-breathing interventions likewise become more difficult to follow as driving complexity increases [65]. Our findings extend this literature by showing that TOS support can be *conditionally useful but fragile*: it may begin when regulation is highly relevant, yet also when the user has fewer resources available to take advantage of it.

7.3 Ruling Out a Simple Familiarization Explanation

Before interpreting this timing difference as evidence about receptivity, we need to rule out a simpler explanation. The preemptive condition did not only change *when* the airflow guidance was introduced relative to receptivity - it also gave participants more cycles of exposure to the airflow rhythm before traffic began, and it may have functioned as an implicit warning that a stressor was coming. Any of these three factors, not receptivity timing itself, could in principle explain why preemptive guidance outperformed TOS guidance, and our design does not allow us to fully separate them.

Two pieces of evidence argue against a purely familiarization-based account, though neither is conclusive. First, breathing-rate reduction did not differ between TOS and preemptive guidance (Section 6.1): if extra pre-traffic cycles simply helped participants get better at the breathing exercise, we would expect to see it show up here, and we do not. Second, the preemptive RMSSD advantage remained reliable even after statistically adjusting for concurrent breathing-rate change. Neither result rules out familiarization or anticipatory-warning effects operating through some

other, non-respiratory pathway - doing so would require a design that manipulates pre-exposure duration and warning content independently of onset timing.

7.4 Event-Relative Onset Timing Within a JIT Framework

These findings tell us *when* the airflow guidance was introduced mattered - they do not tell us *why*, at a mechanistic level, it mattered. We did not directly measure moment-to-moment receptivity, regulatory need, or predicted demand. Instead, the pattern of similar breathing adaptation across both active conditions, paired with better downstream outcomes under preemptive initiation, suggests that how well an intervention works depends not only on whether it is needed, but on whether the person can actually use it right then.

This is a timing question within, rather than a redefinition of, the JITAI framework. In predictable high-demand situations, future demand may become actionable before acute need peaks, opening a window in which a subtle airflow guidance can start while users still have enough capacity to notice, interpret, and adapt to it. Preemptive initiation is one possible JIT strategy for this kind of foreseeable event; TOS initiation is another. Neither should be assumed to be universally better.

Both active conditions reduced breathing rate by a similar amount, but only preemptive guidance produced a reliable RMSSD improvement over baseline, together with lower perceived mental demand relative to TOS guidance. Participants frequently described the earlier airflow guidance as giving them time to prepare before traffic demand increased. TOS guidance could still feel helpful in the moment, but was more exposed to attentional competition and mistimed delivery once the stressful event had already begun.

This study tested one preemptive lead time against onset-triggered initiation. It does not establish an optimal lead time, and we did not directly measure momentary receptivity. Perceived mental demand and participants' accounts of timing fit and attentional competition should be read as evidence relevant to receptivity, not as direct measurements of it. Future work should test multiple lead times and directly estimate momentary receptivity to identify the boundary conditions for each strategy.

7.5 Designing for Opportunity, Not Only Need

Our findings suggest that adaptive affective systems should reason not only about *when users need support*, but also about *when users are able to use it*. This distinction is consistent with the Just-in-Time Adaptive Intervention (JITAI) framework, which emphasizes that intervention effectiveness depends on both states of vulnerability or opportunity and states of receptivity[38]. In high-demand contexts, these states may diverge: the moment when support is most needed may also be a moment when users have fewer attentional resources available to engage with a new intervention [30, 47, 65].

We therefore argue for a shift from *need detection* toward *intervention opportunity estimation*: identifying moments when we can already tell that demand is about to rise, while the person is still able to take in support. In driving, this is plausible because upcoming stressors and task demands can sometimes be anticipated from road context, traffic information, and driver-state signals. Prior work shows that driver stress can sometimes be predicted before the event itself [14], that advance warning of congestion can change subsequent frustration-related driving behavior [26], and that predictable road hazards trigger anticipatory physiological and behavioral responses before the hazard occurs [28]. At the same time, how open drivers are to secondary information or wellbeing prompts still changes with the momentary driving context [30, 47].

For predictable events such as congestion, merges, or navigation-predicted slowdowns, this information may create an opportunity to introduce low-effort regulatory support before attentional demand peaks. By contrast, sudden and unpredictable hazards may still require reactive support. We therefore see preemptive and TOS initiation as complementary JIT strategies, each appropriate under different conditions of event predictability and momentary receptivity, rather than assuming either is universally better. This principle may also extend beyond driving. Proactive-coping studies in medical and performance settings show that regulation initiated before a known stressor can alter subsequent psychological and physiological responses [45, 46]. The design objective, then, is not simply to intervene earlier, but to find moments when support is both *warranted* and *usable*. This shifts the central design question from "When does the user need help?" to "When is there an opportunity for that help to be effectively taken up?"

8 Limitations and Future Work

8.1 Individual Differences and Repeated Exposure

Participants varied substantially in how readily they adapted their breathing to the airflow guidance, how strongly they responded to the traffic stressor, and how they interpreted the intervention subjectively. Although the within-subject design helped control for stable between-participant differences, the modest sample size limited our ability to characterize heterogeneous response profiles or to test potential moderators such as prior breathing experience, driving experience, baseline physiological reactivity, or individual differences in attentional capacity. Future work should replicate the timing comparison with larger samples and examine whether distinct responder profiles emerge across intervention timings.

A second limitation concerns repeated exposure to the same stressful driving scenario. Each participant encountered the traffic event three times under different intervention conditions. Holding the scenario constant strengthened comparability across conditions, but it also introduced the possibility of habituation, learning, and anticipatory familiarity. Although trial order was included in the statistical models, repeated exposure may still have altered stress reactivity or task strategy across drives. Future studies should use multiple stress-equivalent scenarios, vary the location or form of stressful events, or employ larger counterbalanced scenario sets while preserving comparable task difficulty across conditions.

8.2 Intervention and Context Generalizability

The controlled timing experiment evaluated a single regulatory modality: rhythmic airflow guidance delivered during simulated highway driving. Accordingly, the observed timing pattern may not generalize directly to other respiratory-guidance modalities, such as auditory, vibrotactile, visual, or multimodal airflow cues, or to other driving contexts such as urban traffic, intersection negotiation, parking, or emergency maneuvers.

Future work should therefore test whether event-relative timing effects replicate across intervention modalities and driving contexts.

8.3 Statistical Power and Sample Size

A related concern is the sensitivity of the primary RMSSD effect to two influential cardiac observations (Section 6.1, Appendix C). This sensitivity, however, was substantially reduced when using continuous downweighting (Huber robust regression) rather than binary exclusion: the preemptive–TOS contrast remained reliable ($p = .020$) even when both influential observations were retained, albeit with a more conservative effect size ($d = 0.5$ rather than 0.9). We interpret

this convergence across exclusion-based, bootstrap, and robust-regression approaches as evidence that the direction of the effect is unlikely to be a pure artifact of two data points, while still cautioning that the precise magnitude remains uncertain given the sample size. Future work with larger samples is needed to establish a stable effect-size estimate.

8.4 Receptivity Was Inferred Rather Than Directly Measured

The event-relative onset account treats receptivity as a dynamic state reflecting the user's capacity to notice, interpret, and incorporate support. In the present study, receptivity was not measured continuously or manipulated independently. Instead, we examined indirect indicators relevant to receptivity, including perceived mental demand and participants' accounts of timing fit and attentional competition.

8.5 From Physiological Regulation to Driving Performance

The present work focused primarily on respiratory adaptation, cardiac outcomes, perceived workload, and users' experience of intervention timing. It was not designed to determine whether these regulation-related benefits translate into measurable improvements in driving performance or safety. Specifically, the current analyses do not establish whether preemptive guidance improves lane keeping, braking behavior, hazard response, headway maintenance, maneuver quality, or recovery following stressful events.

This distinction is important because physiological regulation should not be assumed to imply improved task performance. Future work should therefore integrate performance-sensitive driving measures and examine whether timing-sensitive respiratory support can improve self-regulation without introducing behavioral costs. Ultimately, opportunity-aware intervention timing should be evaluated not only by whether it changes physiology, but by whether it supports regulation while preserving or improving safe task performance.

9 Conclusion

This study examined how the event-relative onset of airflow-based breathing guidance is associated with regulation-related outcomes during stressful simulated driving. Study 1 was a formative scenario-selection study that identified a manual-driving traffic context with a clearer stress-related profile than the autonomous-driving condition in this sample. Study 2 then used a within-subject design to compare no-guidance baseline driving, TOS guidance, and guidance initiated 45 seconds before predictable traffic onset (preemptive guidance).

Both active guidance conditions were associated with reduced breathing rate relative to baseline, and the two active conditions did not reliably differ in the magnitude of breathing-rate reduction. However, in this simulator setting, only preemptive guidance was associated with a reliable RMSSD improvement relative to baseline, and this improvement exceeded that observed under TOS guidance; preemptive guidance was also associated with lower perceived mental demand than TOS guidance. Participants also frequently described the earlier airflow guidance as giving them time to notice, become familiar with, and incorporate the airflow rhythm before traffic demand increased. In contrast, TOS guidance was sometimes experienced as helpful in the moment but was more often described as abrupt, mistimed, or difficult to incorporate when driving demands were already high.

Together, these findings suggest that respiratory entrainment alone may not fully characterize the outcomes of affective interventions in high-demand tasks. Similar reductions in breathing rate can be accompanied by different downstream cardiac and perceived-workload outcomes when guidance begins at different points relative to a predictable stressor. Within a JIT framework, this suggests that predictable events may permit airflow guidance initiation before acute task demand peaks, when users may have greater capacity to notice and adapt to support.

At the same time, the present study does not directly measure receptivity or establish the mechanism underlying the observed condition differences. Because the preemptive condition also provided pre-event exposure to the airflow rhythm, its effects may reflect event-relative timing, familiarization with the airflow guidance, anticipatory preparation, or a combination of these factors. In addition, the study examined physiological and perceived-workload outcomes rather than driving performance or safety. Future work should directly measure momentary receptivity, compare multiple pre-event lead times, separate predictive signaling from breathing guidance, and evaluate whether opportunity-aware interventions can support both self-regulation and driving performance.

More broadly, these results motivate adaptive systems that consider not only when users may need support, but also when that support can be effectively taken up. For predictable traffic stressors, preemptive initiation may be a useful JIT timing strategy alongside TOS or reactive initiation, rather than a universally superior replacement for them.

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References

[1] 2023. From Lung to Brain: Respiration Modulates Neural and Mental Activity. *Neuroscience & Biobehavioral Reviews* (2023).

[2] Piotr D. Adamczyk and Brian P. Bailey. 2004. If Not Now, When?: The Effects of Interruption at Different Moments Within Task Execution. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 271–278. doi:10.1145/985692.985727

[3] Sufyan Ashhad, Kaiwen Kam, Christopher A Del Negro, and Jack L Feldman. 2022. Breathing rhythm and pattern and their influence on emotion. *Annual review of neuroscience* 45 (2022), 223–247.

[4] Stephanie Balters, Matthew L. Mauriello, So Yeon Park, James A. Landay, and Pablo E. Paredes. 2020. Calm Commute: Guided Slow Breathing for Daily Stress Management in Drivers. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 1 (March 2020), 1–19. doi:10.1145/3380998

[5] Douglas Bates, Martin Mächler, Ben Bolker, and Steve Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* 67, 1 (2015), 1–48. doi:10.18637/jss.v067.i01

[6] Roy F Baumeister. [n. d.]. Choking Under Pressure: Self-Consciousness and Paradoxical Effects of Incentives on Skillful Performance. ([n. d.]).

[7] Matthias Beggiato, Franziska Hartwich, and Josef Krems. 2019. Physiological correlates of discomfort in automated driving. 66 (2019), 445–458. doi:10.1016/j.trf.2019.09.018

[8] Luciano Bernardi, Cesare Porta, Alessandra Gabutti, Lucia Spicuzza, and Peter Sleight. 2001. Modulatory effects of respiration. *Autonomic neuroscience* 90, 1-2 (2001), 47–56.

[9] Johan Bjureberg and James J. Gross. 2021. Regulating road rage. 15, 3 (2021), e12586. doi:10.1111/spc3.12586

[10] Margaret M. Bradley and Peter J. Lang. 1994. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry* 25, 1 (March 1994), 49–59. doi:10.1016/0005-7916(94)90063-9

[11] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3, 2 (Jan. 2006), 77–101. doi:10.1191/1478088706qp063oa

[12] Francesco Casciaro, Vincenza Laterza, Sergio Conte, Maria Pieralice, Antonio Federici, Orlando Todarello, Franco Orsucci, and Elio Conte. 2013. Alpha-rhythm stimulation using brain entrainment enhances heart rate variability in subjects with reduced HRV. *World Journal of Neuroscience* 03, 04 (2013), 213–220. doi:10.4236/wjns.2013.34028 Publisher: Scientific Research Publishing, Inc..

[13] Kyung Yun Choi, Jinmo Lee, Neska ElHaouij, Rosalind Picard, and Hiroshi Ishii. 2021. aSpire: Clippable, Mobile Pneumatic-Haptic Device for Breathing Rate Regulation via Personalizable Tactile Feedback. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, 2021-05-08). ACM, 1–8. doi:10.1145/3411763.3451602

[14] Joseph Clark, Rajdeep Kumar Nath, and Himanshu Thapliyal. 2021. Machine Learning Based Prediction of Future Stress Events in a Driving Scenario. In *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)*. IEEE, 455–458. doi:10.1109/WF-IoT51360.2021.9595098

[15] Joseph Clark, Rajdeep Kumar Nath, and Himanshu Thapliyal. 2021. Machine Learning Based Prediction of Future Stress Events in a Driving Scenario. In *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)*. IEEE, 455–458. doi:10.1109/WF-IoT51360.2021.9595098

[16] Aodhagán Conlon, Rachel Arnold, Ezio Preatoni, and Lee J. Moore. 2022. Pulling the Trigger: The Effect of a 5-Minute Slow Diaphragmatic Breathing Intervention on Psychophysiological Stress Responses and Pressurized Pistol Shooting Performance. 44, 3 (2022), 206–219. doi:10.1123/jsep.2021-0213 Publisher: Human Kinetics.

[17] Jean Costa, Alexander T Adams, Malte F Jung, François Guimbretière, and Tanzeem Choudhury. 2016. EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In *Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing*. 758–769.

[18] Jean Costa, François Guimbretière, Malte F. Jung, and Tanzeem Choudhury. 2019. BoostMeUp: Improving Cognitive Performance in the Moment by Unobtrusively Regulating Emotions with a Smartwatch. 3, 2 (2019), 1–23. doi:10.1145/3328911

[19] Michael W Eysenck, Nazanin Derakshan, Rita Santos, and Manuel G Calvo. 2007. Anxiety and cognitive performance: attentional control theory. *Emotion* 7, 2 (2007), 336.

[20] Tan Gemicioglu, Thalia Viranda, Yiran Zhao, Olzhas Yessenbayev, Jatin Arora, Jane Wang, Pedro Lopes, Alexander T. Adams, and Tanzeem Choudhury. 2024. BreathePulse: Peripheral Guided Breathing via Implicit Airflow Cues for Information Work. 8, 4 (2024), 1–33. doi:10.1145/3702211

[21] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology*. Vol. 52. Elsevier, 139–183. doi:10.1016/S0166-4115(08)62386-9

[22] Xiaolin He, Jork Stapel, Meng Wang, and Riender Happee. 2022. Modelling perceived risk and trust in driving automation reacting to merging and braking vehicles. 86 (2022), 178–195. doi:10.1016/j.trf.2022.02.016

[23] Hsiu-Fang Hsieh and Sarah E. Shannon. 2005. Three approaches to qualitative content analysis. *Qualitative Health Research* 15, 9 (2005), 1277–1288. doi:10.1177/1049732305276687

[24] Shamsi T Iqbal and Brian P Bailey. 2005. Investigating the effectiveness of mental workload as a predictor of opportune moments for interruption. In *CHI'05 extended abstracts on Human factors in computing systems*. 1489–1492.

[25] W. J. Trost, C. Labbé, and D. Grandjean. 2017. Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia* 96 (Feb. 2017), 96–110. doi:10.1016/j.neuropsychologia.2017.01.004 Publisher: Elsevier BV.

[26] Mark B. Johnson and Scott McKnight. 2009. Warning Drivers About Potential Congestion as a Means to Reduce Frustration-Driven Aggressive Driving. *Traffic Injury Prevention* 10, 4 (2009), 354–360. doi:10.1080/15389580902969765

[27] Laora Kerautret, Stephanie Dabic, and Jordan Navarro. 2022. Detecting Driver Stress and Hazard Anticipation Using Real-Time Cardiac Measurement: A Simulator Study. *Brain and Behavior* 12, 2 (2022), e2424. doi:10.1002/brb3.2424

[28] Laora Kerautret, Stephanie Dabic, and Jordan Navarro. 2023. Exploring Hazard Anticipation and Stress While Driving in Light of Defensive Behavior Theory. *Scientific Reports* 13, 1 (2023), 7883. doi:10.1038/s41598-023-34714-7

[29] Daniel S. Kluger et al. 2022. Recent insights into respiratory modulation of brain activity offer new perspectives on cognition and emotion. *Biological Psychology* 170 (2022), 108316. doi:10.1016/j.biopsycho.2022.108316

[30] Kevin Koch, Varun Mishra, Shu Liu, Thomas Berger, Elgar Fleisch, David Kotz, and Felix Wortmann. 2021. When Do Drivers Interact with In-Vehicle Well-being Interventions?: An Exploratory Analysis of a Longitudinal Study on Public Roads. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 1 (2021), 1–30. doi:10.1145/3448116

[31] Alexandra Kuznetsova, Per B. Brockhoff, and Rune H. B. Christensen. 2017. lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software* 82, 13 (2017), 1–26. doi:10.18637/jss.v082.i13

[32] Sylvain Laborde, Mark S. Allen, Uirassu Borges, Fabrice Dosseville, Timo J. Hosang, Martin Iskra, Emma Mosley, Claudia Salvotti, Luca Spolverato, Nicole Zammit, and Florian Javelle. 2022. Effects of voluntary slow breathing on heart rate and heart rate variability: A systematic review and a meta-analysis. *Neuroscience & Biobehavioral Reviews* 138 (2022), 104711. doi:10.1016/j.neubiorev.2022.104711

[33] Pierrick Laulan and Ulrike Rimmele. 2026. Breathing Slower Is Not Always Better: Slow-Paced Breathing Enhances Heart Rate Variability but Produces Age-Differential Effects on Emotional Reactivity and Memory. *International Journal of Psychophysiology* 226 (2026), 113418. doi:10.1016/j.ijpsycho.2026.113418

[34] Jinmo Lee, Neska Elhaouij, and Rosalind Picard. 2021. AmbientBreath: Unobtrusive Just-in-time Breathing Intervention Using Multi-sensory Stimulation and Its Evaluation in a Car Simulator. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 2 (2021), 1–30. doi:10.1145/3463493

[35] Russell V. Lenth and Julia Piaskowski. 2026. *emmeans: Estimated Marginal Means, aka Least-Squares Means.* https://rvlenth.github.io/emmeans/ R package.

[36] Zheng Ma and Yiqi Zhang. 2021. Drivers trust, acceptance, and takeover behaviors in fully automated vehicles: Effects of automated driving styles and driver's driving styles. 159 (2021), 106238. doi:10.1016/j.aap.2021.106238

[37] Inbal Nahum-Shani, Eric B. Hekler, and Donna Spruijt-Metz. 2015. Building Health Behavior Models to Guide the Development of Just-in-Time Adaptive Interventions: A Pragmatic Framework. *Health Psychology* 34, S (2015), 1209–1219. doi:10.1037/hea0000306

[38] Inbal Nahum-Shani, Shawna N Smith, Bonnie J Spring, Linda M Collins, Katie Witkiewitz, Ambuj Tewari, and Susan A Murphy. 2016. Just-in-time adaptive interventions (JITAIs) in mobile health: key components and design principles for ongoing health behavior support. *Annals of behavioral medicine* (2016), 1–17.

[39] Inbal Nahum-Shani, Shawna N. Smith, Bonnie J. Spring, Linda M. Collins, Katie Witkiewitz, Ambuj Tewari, and Susan A. Murphy. 2018. Just-in-Time Adaptive Interventions (JITAIs) in Mobile Health: Key Components and Design Principles for Ongoing Health Behavior Support. *Annals of Behavioral Medicine* 52, 6 (2018), 446–462. doi:10.1007/s12160-016-9830-8

[40] Odmar Neumann. 1996. Theories of attention. In *Handbook of perception and action*. Vol. 3. Elsevier, 389–446.

[41] Simplice Igor Noubissie Tientcheu, Shengzhi Du, and Karim Djouani. 2022. Review on Haptic Assistive Driving Systems Based on Drivers' Steering-Wheel Operating Behaviour. *Electronics* 11, 13 (July 2022), 2102. doi:10.3390/electronics11132102

[42] Pablo E. Paredes, Yijun Zhou, Nur Al-Huda Hamdan, Stephanie Balters, Elizabeth Murnane, Wendy Ju, and James A. Landay. 2018. Just Breathe: In-Car Interventions for Guided Slow Breathing. 2, 1 (2018), 1–23. doi:10.1145/3191760

[43] Polar Electro Oy. 2024. Polar H10 Heart Rate Sensor. https://www.polar.com/us-en/sensors/h10-heart-rate-sensor Accessed: 2025-08-15.

[44] Alexander Rasch, Christian-Nils Boda, Prateek Thalya, Tobias Aderum, Alessia Knauss, and Marco Dozza. 2020. How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers? 142 (2020), 105569. doi:10.1016/j.aap.2020.105569

[45] Sophie Schlatter, Laura Schmidt, Marc Lilot, Aymeric Guillot, and Ursula Debarnot. 2021. Implementing biofeedback as a proactive coping strategy: Psychological and physiological effects on anticipatory stress. *Behaviour Research and Therapy* 140 (2021), 103834.

[46] Sophie T. Schlatter, Corentin C. Thérond, Aymeric Guillot, Simon P. Louisy, Antoine Duclos, Jean-Jacques Lehot, Thomas Rimmelé, Ursula S. Debarnot, and Marc E. Lilot. 2022. Effects of relaxing breathing paired with cardiac biofeedback on performance and relaxation during critical simulated situations: a prospective randomized controlled trial. *BMC Medical Education* 22, 1 (Dec. 2022). doi:10.1186/s12909-022-03420-9 Publisher: Springer Science and Business Media LLC.

[47] Rob Semmens, Nikolas Martelaro, Pushyami Kaveti, Simon Stent, and Wendy Ju. 2019. Is Now A Good Time?: An Empirical Study of Vehicle-Driver Communication Timing. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 1–12. doi:10.1145/3290605.3300867

[48] Caroline Sevoz-Couche and Sylvain Laborde. 2022. Heart rate variability and slow-paced breathing: when coherence meets resonance. *Neuroscience & Biobehavioral Reviews* 135 (2022), 104576.

[49] Robin Shao, Idy S. C. Man, and Tatia M. C. Lee. 2024. The Effect of Slow-Paced Breathing on Cardiovascular and Emotion Functions: A Meta-Analysis and Systematic Review. 15, 1 (2024), 1–18. doi:10.1007/s12671-023-02294-2

[50] Olger Siebinga, Arkady Zgonnikov, and David A. Abbink. 2023. Merging in a Coupled Driving Simulator: How do drivers resolve conflicts? doi:10.48550/arXiv.2308.04842 arXiv:2308.04842 [cs].

[51] Mark Span. 2025. *PolarBand2lsl*. https://github.com/markspan/PolarBand2lsl

[52] Charles D Spielberger and Fernando Gonzalez-Reigosa. [n. d.]. DEVELOPMENT OF THE SPANISH EDITION OF THE STATE-TRAIT ANXIETY INVENTORY. ([n. d.]).

[53] Sylwia Sumińska, Andrzej Rynkiewicz, and Mikołaj Szulczewski. 2026. Resonance Frequency Versus Fixed 0.1 Hz Breathing in HRV Biofeedback: A Four-Week Randomized Comparison. *Scientific Reports* 16 (2026), 22630. doi:10.1038/s41598-026-53333-6

[54] Aaron Tabor, Scott Bateman, Erik J. Scheme, and M. C. Schraefel. 2022. Comparing Heart Rate Variability Biofeedback and Simple Paced Breathing to Inform the Design of Guided Breathing Technologies. *Frontiers in Computer Science* 4 (2022). doi:10.3389/fcomp.2022.926649

[55] Vernier Science Education. 2024. *Go Direct Respiration Belt*. Beaverton, OR. https://www.vernier.com/product/go-direct-respiration-belt/ Accessed: 2025-08-15.

[56] Katherine Vytal, Brian Cornwell, Nicole Arkin, and Christian Grillon. 2012. Describing the interplay between anxiety and cognition: From impaired performance under low cognitive load to reduced anxiety under high load. *Psychophysiology* 49, 6 (June 2012), 842–852. doi:10.1111/j.1469-8986.2012.01358.x Publisher: Wiley.

[57] Huanjie Wang, Wenshuo Wang, Shihua Yuan, Xueyuan Li, and Lijun Sun. 2022. On Social Interactions of Merging Behaviors at Highway On-Ramps in Congested Traffic. *IEEE Transactions on Intelligent Transportation Systems* 23, 8 (Aug. 2022), 11237–11248. doi:10.1109/TITS.2021.3102407 arXiv:2008.06156 [cs].

[58] Xuesong Wang, Minming Yang, and David Hurwitz. 2019. Analysis of cut-in behavior based on naturalistic driving data. 124 (2019), 127–137. doi:10.1016/j.aap.2019.01.006

[59] Christopher D. Wickens. 2008. Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50, 3 (June 2008), 449–455. doi:10.1518/001872008X288394

[60] Jinchun Wu, Zelei Pan, Yixuan Liu, Quan Chen, Feng Zang, Annette Chabebe, and Chengqi Xue. [n. d.]. Non-Visual Effects of Road Lighting CCT on Driver's Mood, Alertness, Fatigue and Reaction Time: A Comprehensive Neuroergonomic Evaluation Study. ([n. d.]).

[61] Yueru Xu, Shan Bao, and Anuj K. Pradhan. 2021. Modeling drivers' reaction when being tailgated: A Random Forests Method. 78 (2021), 28–35. doi:10.1016/j.jsr.2021.05.004

[62] Robert M. Yerkes and John D. Dodson. 1908. The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology* 18, 5 (Nov. 1908), 459–482. doi:10.1002/cne.920180503 Publisher: Wiley.

[63] Sebastian Zepf, Po-Wen Kao, Jan-Peter Kramer, and Philipp Scholl. 2021. Breath-Triggered Haptic and Acoustic Guides to Support Effortless Calm Breathing. In *2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, Mexico, 1796–1800. doi:10.1109/EMBC46164.2021.9629766

[64] Yutong Zhang, Edmond Awad, Morgan R. Frank, Peng Liu, and Na Du. 2024. Understanding Human-machine Cooperation in Game-theoretical Driving Scenarios amid Mixed Traffic. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. doi:10.1145/3613904.3642053

[65] Xin Zhou, Gang He, Honghai Zhu, Yi Wang, and Wei Zhang. 2024. Evaluation of driver stress intervention with guided breathing and positive comments. *Applied Ergonomics* 114 (Jan. 2024), 104144. doi:10.1016/j.apergo.2023.104144

A Formal Study

A.1 Experimental Design and Procedure

We conducted a within-subject driving simulator study to evaluate whether the empirically grounded traffic scenario elicited stronger arousal in autonomous vehicle (AV) or human-driven vehicle (HV) mode. Participants experienced two identical stressful traffic scenarios, once in AV mode and once in HV mode, with mode order counterbalanced. Participants completed pre-drive SAM, STAI-derived state-anxiety items, and demographic measures before driving.

Participants were fitted with a Polar H10 ECG sensor and a Vernier Go Direct Respiration Belt. Each simulation began with a baseline driving period without vehicle interactions or interventions, followed by a stressful traffic scenario based on high-arousal events identified through prior research, and then a recovery period.

A.2 Physiological Measures

A.2.1 Heart Rate and Heart-Rate Variability. ECG data were segmented into task-aligned windows using keyboard-triggered event markers synchronized with the driving simulator. The windows included a no-traffic baseline period and a time-of-interest window containing heavy traffic and, when applicable, airflow breathing guidance.

We visually inspected raw ECG signals and RR-interval series before cardiac analysis. Segments showing substantial signal loss, motion artifact, or unreliable R-peak detection were excluded. For retained ECG segments, R-peaks were detected using the NeuroKit2 `ecg_process` pipeline. Heart rate was derived from mean inter-beat intervals, and heart-rate variability was quantified using RMSSD.

Because breathing rate can influence RMSSD through respiratory sinus arrhythmia, we interpret RMSSD conservatively as a respiration-coupled cardiac autonomic outcome rather than as a respiration-independent measure of stress recovery.

A.2.2 Breathing Rate. Breathing force was recorded using the Vernier Go Direct Respiration Belt. To estimate breathing rate, the force signal was smoothed, band-pass filtered to the typical breathing-frequency range, and analyzed using peak detection. Breathing rate was calculated from the mean interval between successive detected respiratory peaks.

In this paper, we use *respiratory entrainment* to refer to systematic adjustment of participants' spontaneous breathing rate toward the slower externally imposed airflow rhythm. Because we analyze breathing-rate change rather than cycle-level phase locking, we do not use the term to imply strict oscillatory synchronization.

A.3 Psychological Measures

A.3.1 Arousal and Valence. We assessed affective state using the Self-Assessment Manikin (SAM). Participants rated arousal and valence on 9-point scales. Higher arousal scores indicate greater arousal; higher valence scores indicate greater unpleasantness.

A.3.2 State Anxiety. To assess momentary anxiety while limiting repeated survey burden, we used an investigator-selected nine-item subset of the State Anxiety scale of the State–Trait Anxiety Inventory. Items were rated using the original 4-point response format from (1) *Not at all* to (4) *Very much so*. The anxiety-absent item was reverse-scored so that higher composite scores indicated greater state anxiety. Because this subset was investigator-selected rather than a previously validated short form, we refer to the resulting measure as a nine-item STAI-derived state-anxiety composite.

Internal consistency was acceptable to good across administrations. Cronbach's α was .79 for pre-drive responses and .83 for post-drive responses; when pre- and post-drive administrations were pooled, α was .82. Approximate McDonald's ω showed a similar pattern (.85, .89, and .88, respectively).

Table 5. Internal consistency of the nine-item STAI-derived state-anxiety composite.

Administration	N	Cronbach's α	Approx. McDonald's ω
Pre-drive	65	.79	.85
Post-drive	66	.83	.89
Pre + post pooled	131	.82	.88

A.4 Study 1 Results

Manual driving showed a clearer cardiac stress profile than autonomous driving. In the HV condition, RMSSD decreased significantly, whereas the corresponding change in AV was not significant. HR increased significantly in HV but not AV. Breathing-rate responses showed a different pattern, with BR increasing more clearly in AV. These findings supported using the manual-driving traffic scenario as the common stress context for Study 2.

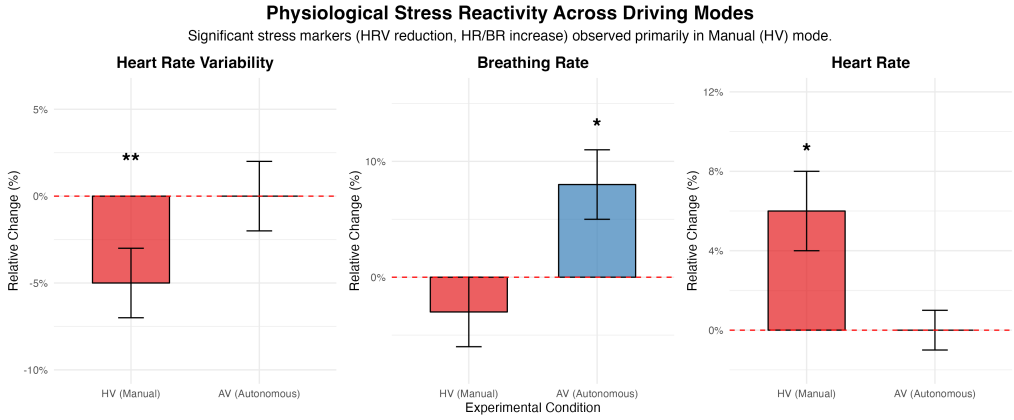


Fig. 9. Relative percentage changes in HRV, breathing rate, and heart rate from no-guidance control to stressful traffic driving in manual and autonomous driving modes.

B Survey Sensitivity Analyses

Because SAM and STAI use ordinal response scales, we conducted non-parametric sensitivity analyses using paired Wilcoxon signed-rank tests on raw pre- and post-drive responses within each condition. SAM arousal increased significantly from pre- to post-drive in all three conditions. SAM valence also shifted significantly toward greater unpleasantness in all three conditions. For the STAI-derived state-anxiety composite, only TOS showed a significant pre-post increase after correction.

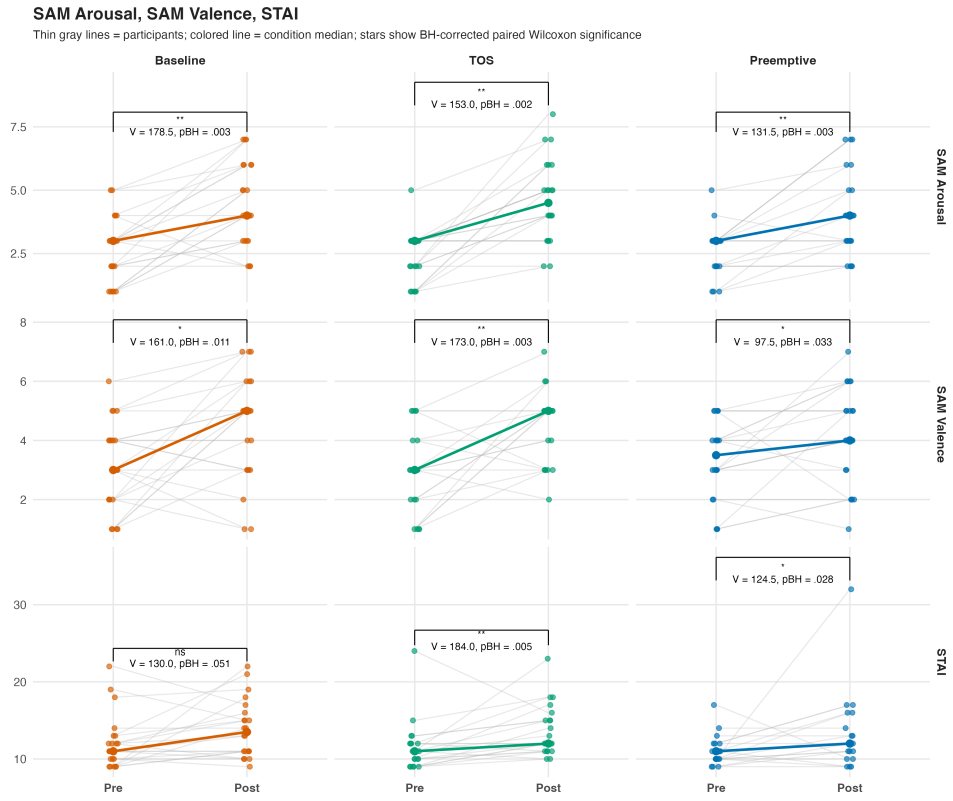


Fig. 10. *Pre- and post-drive affect and anxiety by condition.* Thin gray lines represent individual participants, blue points show individual responses, and orange lines indicate group medians. Brackets denote within-condition pre-post differences based on paired Wilcoxon signed-rank tests with Benjamini-Hochberg correction.

C Cardiac Data Quality and Sensitivity Analyses

C.1 Cardiac Data-Quality and Influence Screening

Before inferential modeling, cardiac-derived percentage-change values were screened using a conservative 3×IQR influence rule. This screening identified two influential cardiac cases. P4 showed a clear RR-interval artifact in the TOS analysis window, consistent with ECG/R-peak detection error inflating RMSSD estimates. P17 did not show the same clear raw-ECG artifact, but produced an extreme cardiac-derived percentage-change value under the same influence-screening rule.

Accordingly, the primary HRV and HR analyses used a conservative cardiac-analysis sample excluding P4 and P17. Breathing-rate analyses retained all available physiological participants because these exclusions were specific to cardiac-derived measures. To evaluate robustness, we repeated the HRV analyses with P4 and P17 retained, with only observation-level 3×IQR outliers removed, and using log-transformed RMSSD change. The pre-emptive–TOS HRV contrast remained directionally consistent across models, although the full-inclusion model was more conservative.

C.2 Respiration-Adjusted HRV Sensitivity Analysis

Because RMSSD can be affected by respiration, we conducted a respiration-adjusted sensitivity analysis to test whether the pre-emptive HRV advantage was explained by concurrent breathing-rate change. Using the primary cardiac-analysis sample excluding P4 and P17, we re-estimated the RMSSD percentage-change model with concurrent breathing-rate percentage change as a mean-centered covariate.

In the model including all three conditions, the adjusted pre-emptive–TOS contrast remained statistically reliable after BH correction ($\beta = 17.50$, $SE = 6.00$, $p_{\mathrm{BH}} = .008$, $d = 0.94$). Pre-emptive guidance also remained higher than no-guidance baseline after respiratory adjustment ($\beta = 22.92$, $SE = 6.99$, $p_{\mathrm{BH}} = .006$, $d = 1.23$), whereas TOS did not differ from baseline ($\beta = 5.42$, $SE = 7.19$, $p_{\mathrm{BH}} = .454$, $d = 0.29$). The breathing-rate covariate itself was not a significant predictor of RMSSD change ($\beta = -0.22$, $SE = 0.15$, $p = .151$), and adding it did not significantly improve model fit, $\chi^2(1) = 2.09$, $p = .149$.

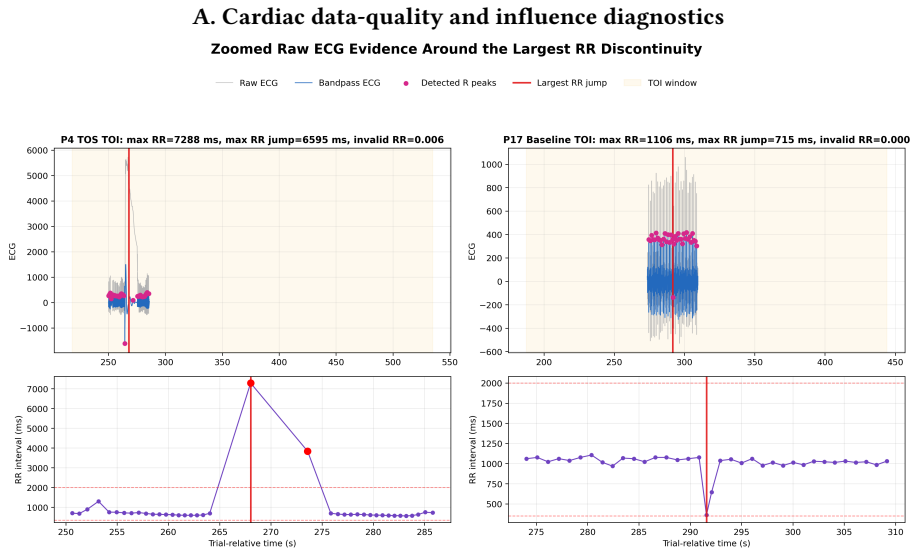
In an intervention-only sensitivity model, the pre-emptive advantage over TOS also remained statistically reliable after adjustment for concurrent breathing-rate change ($\beta = 16.12$, $SE = 5.91$, $p = .011$, $d = 0.91$). These analyses suggest that the pre-emptive RMSSD advantage was not fully explained by concurrent breathing-rate slowing, although they do not establish respiration-independent cardiac effects.

C.3 Bootstrap and Robust Regression Sensitivity Checks

To further evaluate the robustness of the pre-emptive–TOS RMSSD contrast beyond binary exclusion rules, we conducted two additional sensitivity checks. First, we bootstrapped the pairwise contrast (5,000 resamples, participant-level case resampling). In the primary cardiac-analysis sample (excluding P4 and P17), the bootstrap 95% CI for the pre-emptive–TOS difference did not cross zero (Δ=16.9, 95% CI [6.09, 29.2]). When P4 and P17 were retained, the bootstrap CI widened and crossed zero (Δ=10.5, 95% CI [-3.59, 24.8]), reflecting the disproportionate influence of these two observations on a non-robust estimator.

Second, because binary exclusion criteria can appear post-hoc, we re-estimated the pre-emptive–TOS contrast using Huber robust regression, which continuously downweights influential observations rather than removing them via a fixed threshold. Using the full cardiac sample (P4 and P17 retained), the robust-regression contrast remained statistically reliable (Δ=10.3, 95% CI [1.62, 19.0], p=.020). Inspection of the fitted robust weights confirmed that P4's TOS trial and P17's baseline trial received substantially reduced weight, independently corroborating our original 3×IQR-based influence screening without relying on a hard exclusion rule.

Together, these analyses indicate that the pre-emptive–TOS RMSSD difference is not an artifact of a particular exclusion threshold: a continuous-weighting approach that retains all participants still detects a reliable difference, though its magnitude is more conservative (Δ=10, d=0.5) than the point estimate from the primary exclusion-based sample (Δ=17, d=0.9). We report this range rather than treating either estimate as the definitive effect size.



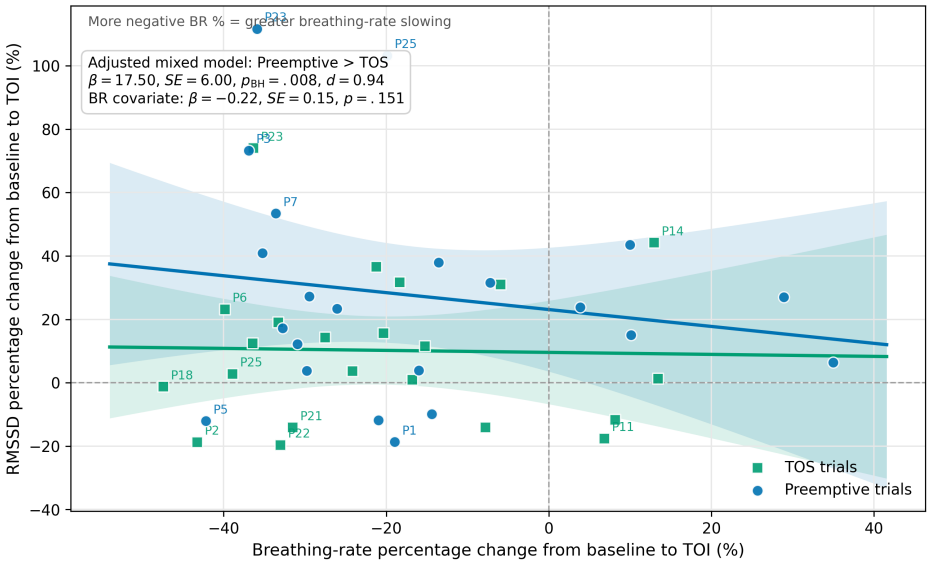


Fig. 11. *Cardiac data-quality and respiration-adjusted sensitivity analyses.* Panel A shows raw ECG and RR-interval diagnostics for influential cardiac cases. P4 showed a clear RR-interval artifact in the TOS analysis window, whereas P17 was treated as an influential cardiac-derived case rather than a clear raw-signal failure. Panel B shows that the pre-emptive RMSSD advantage remained after adjustment for concurrent breathing-rate percentage change. Together, these analyses support the robustness of the HRV pattern while clarifying that the effect should not be interpreted as direct evidence of respiration-independent RSA.

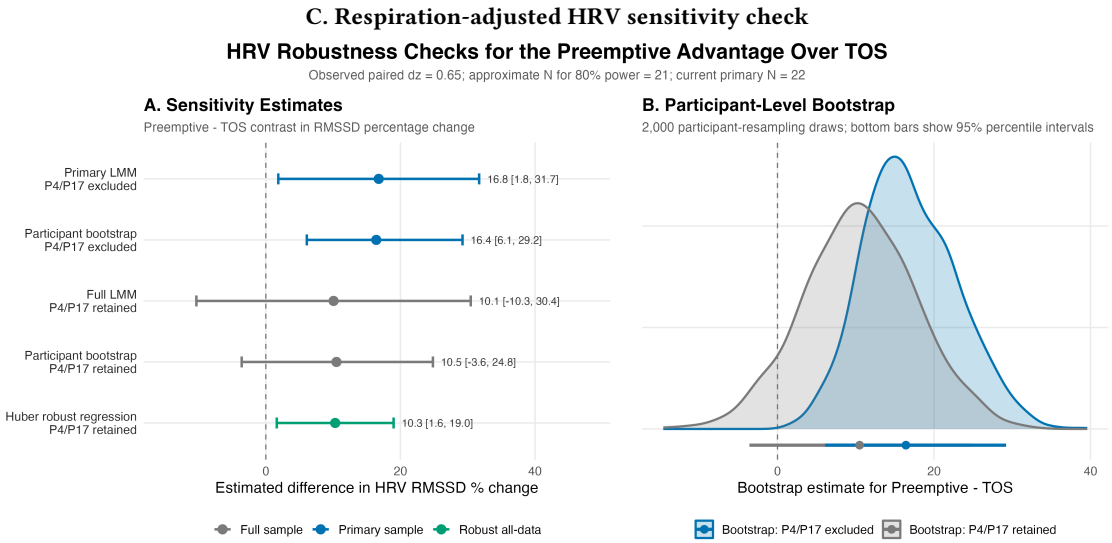


Fig. 12. *HRV robustness checks for the preemptive advantage over TOS.*Panel A summarizes the estimated preemptive–TOS difference in RMSSD percentage change across exclusion-based, bootstrap, full-sample, and Huber robust-regression analyses. Points show estimated contrasts and horizontal bars show uncertainty intervals. Panel B shows participant-level bootstrap distributions for the preemptive–TOS contrast with P4/P17 excluded versus retained. Across analyses, the estimated effect remained positive, but the full-sample bootstrap interval was wider and included zero, indicating that the magnitude of the HRV effect should be interpreted cautiously.