

# A Second Pair of Eyes: Evaluating a Helmet-Integrated Multimodal HMI for Proactive Urban Motorcyclist Safety

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Motorcyclists are among the most vulnerable road users, frequently hindered by late detection of hazards in complex urban traffic. We evaluated MOTEX, a helmet-integrated HMI delivering proactive directional cues through peripheral visual, auditory, and multimodal feedback. In a within-subject simulator study ( $N = 13$ ) in 16 scenarios derived from common accident typologies, no statistically significant effects were found for reaction time ( $p = 0.33$ ) or safety margins ( $p = 0.42$ ). However, visual and multimodal cues yielded numerically faster responses ( $574 \pm 317$  ms and  $570 \pm 360$  ms) compared to the control ( $747 \pm 445$  ms). Approximately 70% of the participants reported increased situation awareness, alongside low cognitive workload and moderate trust—suggesting the system functions as a supportive “second pair of eyes” for spatial confirmation rather than prescriptive warning. These findings demonstrate the feasibility of non-intrusive, decoupled helmet-integrated safety systems as modular retrofits bridging human perception and automated hazard detection.

CCS Concepts: • **Human-centered computing** → **Laboratory experiments; User Studies.**

Additional Key Words and Phrases: Motorcycle Safety, Proactive HMI, Situation Awareness, Multimodal Feedback, Riding Simulation

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## 1 Introduction

Motorcyclists remain one of the most at-risk groups of vulnerable road users (VRUs) worldwide. According to the 3.6 target of the Sustainable Development Goals (SDG) of the World Health Organisation, there is an urgent international mandate to reduce road traffic accidents and deaths by 50% [38]. In the European Union, while overall road fatalities have seen a steady decline, motorcyclist deaths remain disproportionately high, accounting for nearly 18% of all road deaths [8, 12, 13], despite the fact that powered two-wheelers represent approximately 2% of the total passenger kilometres travelled [15]. A primary factor in these incidents is the “Look-but-Fail-to-See” phenomenon (LBFTS), where a hazard is physically visible but fails to be processed cognitively by the rider, often due to the high environmental and cognitive workload of urban navigation [18, 25, 30]. This perceptual failure is compounded in dense urban environments, where the driver must simultaneously manage vehicle control, route planning, and continuous monitoring of a dynamic and unpredictable traffic environment [7, 21].

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The evolution of motorcycle safety technology has historically focused on mitigating the consequences of a rider’s input during a crisis. Anti-lock Braking Systems (ABS) and Traction Control (TC) have transitioned from premium features to mandatory standards for new motorcycles within the EU [14]. Although critical for maintaining stability, these systems remain inherently “reactive”; their intervention is entirely dependent on the rider first perceiving a hazard and initiating a physical input. This creates a dangerous temporal gap in which safety depends on the immediate reaction speed of the rider and the awareness of the situation [39]. Drawing on Endsley’s Situation Awareness (SA) model, this gap can be understood as a failure at the first level of perception: the rider’s ability to detect and attend to environmental elements before they reach a critical threshold [10]. This three-level model—encompassing the perception of environmental elements, the comprehension of their meaning, and the projection of their future state—, combined with the Distributed Situation Awareness (DSA) theory [31], provide a framework for understanding where and how a feed-forward cue can intervene most effectively in the rider’s cognitive loop. Related work on helmet-mounted displays and automotive head-up displays suggests that feed-forward support is promising, but only when information is presented in a way that does not compete with roadway monitoring or narrow the effective visual field of the rider [17, 24, 35]. More recently, radar-based Advanced Rider Assistance Systems (ARAS) have been introduced in production motorcycles, primarily enabled by suppliers such as Bosch. Bosch provides front- and rear-radar modules that support functions such as Adaptive Cruise Control, Blind Spot Detection, and Forward Collision Warning, which have been integrated into flagship models including the BMW R 1250 GS, Ducati Multistrada V4 and KTM Super Adventure [3]. However, these systems typically rely on dashboard-mounted displays or mirror-integrated haptics, which require the rider to divert their gaze from the road to the cockpit, potentially leading to “attentional blink” in critical moments [32]. The fundamental limitation of such cockpit-centric designs is that they impose an additional perceptual task at the precise moment when the rider’s attentional resources are most constrained.

Currently, there is a significant “safety-utility gap” in the market. Commercial smart helmet development has largely prioritised secondary tasks, such as turn-by-turn navigation and multimedia connectivity, rather than safety-critical interaction [5]. Furthermore, research into Helmet-Mounted Displays (HMD) and Head-Up Displays (HUD) has often focused on visual overlays that can contribute to visual saturation [2, 17]. Studies in automotive HUD contexts have similarly demonstrated that visually dense overlays can paradoxically degrade hazard detection performance by narrowing the operator’s functional field of view [23]. This body of evidence suggests that the modality, spatial placement, and semantic content of a safety cue are as consequential as its mere presence.

To address these limitations, we propose a shift towards proactive awareness support, aligned with Euro NCAP’s Vision 2030 for safer mobility [11]. This feed-forward approach aims to provide the rider with a “second pair of eyes”, identifying potential conflicts in and outside peripheral areas. Implementing such a system requires careful management of the high sensory workload. Following Wickens’ Multiple Resource Theory (MRT) and meta-analyses on interruption management [26, 37], we hypothesise that the distribution of information between sensory channels—specifically visual and auditory—can reduce cognitive bottleneck. MRT states that tasks that share the same perceptual modality and processing stage compete for the same finite cognitive resources, while cross-modal task pairings exhibit significantly less interference [36, 37]. This theoretical grounding motivates the decouple design, in which spatial auditory cues complement, rather than replicate, peripheral visual signals.

## 1.1 Aim of Study

The primary objective of this research is to evaluate the efficacy of a helmet-integrated proactive HMI to improve motorcyclist safety during critical urban interactions. To this end, we introduce MOTEX, a helmet-integrated multimodal

HMI that uses a peripheral LED array and integrated helmet speakers. We evaluated the effectiveness of this decouple interface through a high-fidelity simulator study. Although traditional safety systems focus on reactive intervention, this study investigates whether feed-forward multimodal cues—specifically by systematically comparing baseline, visual, auditory, and multimodal feedback—can support a rider’s SA without inducing cognitive overload or behavioural dependency [29]. We define the following research questions:

- **RQ1** (Behavioural): To what extent does the presence of proactive visual, auditory, or multimodal cues influence the physical response metrics of a motorcycle rider?
- **RQ2** (Perceptual): How do motorcycle riders perceive the utility and clarity of different feedback modalities, and which configuration is associated with the highest subjective gain in situational awareness?
- **RQ3** (Design rationale): To what extent does a decouple helmet interface influence a rider’s internal confidence and hazard detection, independent of their response behaviour?

By addressing these questions, we aim to establish a design rationale for safety interfaces that move critical information from the motorcycle’s cockpit directly into the rider’s primary sensory field. This study seeks not only to measure physical safety margins but also to understand the psychological role of HMI as a “second pair of eyes” that validates the internal perception of the rider in urban environments. This work contributes: (1) a functional prototype of a proactive, helmet-integrated artefact; (2) an empirical evaluation of multimodal feedback across critical PTW accident typologies; and (3) a discussion on the role of HMI in validating a rider’s internal perception of risk.

## 2 Method

Fourteen licenced and active motorcycle riders participated in the study ( $M_{age} = 32.9$ ,  $SD = 11.2$ ). Detailed demographic and survey data were available for ten participants (9 male, 4 female). Within the sample, four participants reported regular riding experience (daily or weekly), while the remaining participants reported occasional riding.

The experiment was conducted in a dedicated laboratory setting with controlled ambient lighting to ensure visibility of peripheral LED cues of the helmet. The room was acoustically isolated from external noise to support a clear perception of spatialised auditory feedback. The study was approved by the Ethics Review Board of Eindhoven University of Technology, and all participants gave their informed consent.

### 2.1 Apparatus and Virtual Environment

The experimental setup consisted of a stationary motorcycle simulator combined with a helmet-integrated feedback prototype (MOTEX), as shown in Figure 1. The MOTEX helmet setup is based on the Nolan N60-6 Sport Hotfoot. It followed established motorcycle simulator methodologies such as the MOTORIST platform [4] and related work on rider behaviour by Grottoli et al. [16].

The physical interface consisted of a static motorcycle handlebar assembly equipped with a 12-bit magnetic encoder (AS5600) for steering input, a Sur-Ron electric throttle and an electronic brake lever, both based on potentiometer sensing. These components were selected to provide realistic tactile interaction through familiar control inputs. Sensor data were processed via an Arduino Uno R3 microcontroller at a sampling rate of 50 Hz, enabling accurate capture of steering, throttle, and braking behaviour (see supplementary material).

The virtual environment was developed in Unity 2022.3 and presented from a first-person rider perspective, with the camera rigidly coupled to the motorcycle and a horizontal field of view of 70° (see supplementary material). The participants viewed a simplified motorcycle interface that included handlebars, a rotating front wheel, and a speedometer

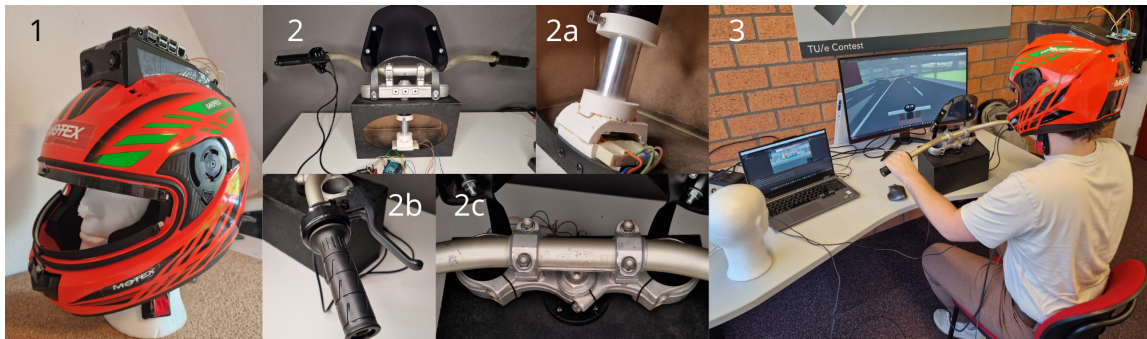


Fig. 1. Image 1: MOTEX prototype. Image 2: stationary motorcycle handlebar assembly, including steering sensor integration (2a), throttle and brake lever (2b), and steering mount (2c). Image 3: laboratory setup showing the simulator, control interface, display, and MOTEX helmet worn by a participant.



Fig. 2. First-person rider perspective within the Unity-based simulator. Multimodal feedback cues (peripheral visual illumination and spatial audio indicator) are overlaid to illustrate how a hazard event is presented to the participant. The speedometer displays the current velocity (51 km/h).

that displays the velocity in km/h. Steering inputs were visually reflected in handlebar and wheel orientation, providing a direct correspondence between physical input and on-screen motion. The environment consisted of a low-poly urban setting with multiple intersections. The scene included buildings of varying size and colour, roadside elements such as trees and benches, and pedestrian pathways (without animated pedestrians). Visual occlusions were deliberately introduced through the environmental layout and placement of objects to partially obstruct approaching traffic.

## 2.2 Scenarios and Cues

Sixteen hazard scenarios were implemented based on four common urban motorcycle crash typologies derived from the SaferWheels framework [27]: cross-traffic from the right (C1), cross-traffic from the left (C2), lateral conflicts through lane intrusion (L2), and opposing vehicles turning across the path of the rider (T7). Each typology was implemented at four distinct locations within the virtual environment, introducing variation in approach direction, road geometry, and relative positioning. For each trial, a hazard vehicle was triggered when the participant crossed an invisible activation point. The trajectory and speed of the hazard vehicle were scripted such that, at the instructed riding speed of 50 km/h, a collision would occur near the centre of the driver’s lane if no evasive action was taken. Hazard vehicles emerged from partially occluded positions and became visible approximately 3–4 s prior to the predicted collision. No other traffic was present.

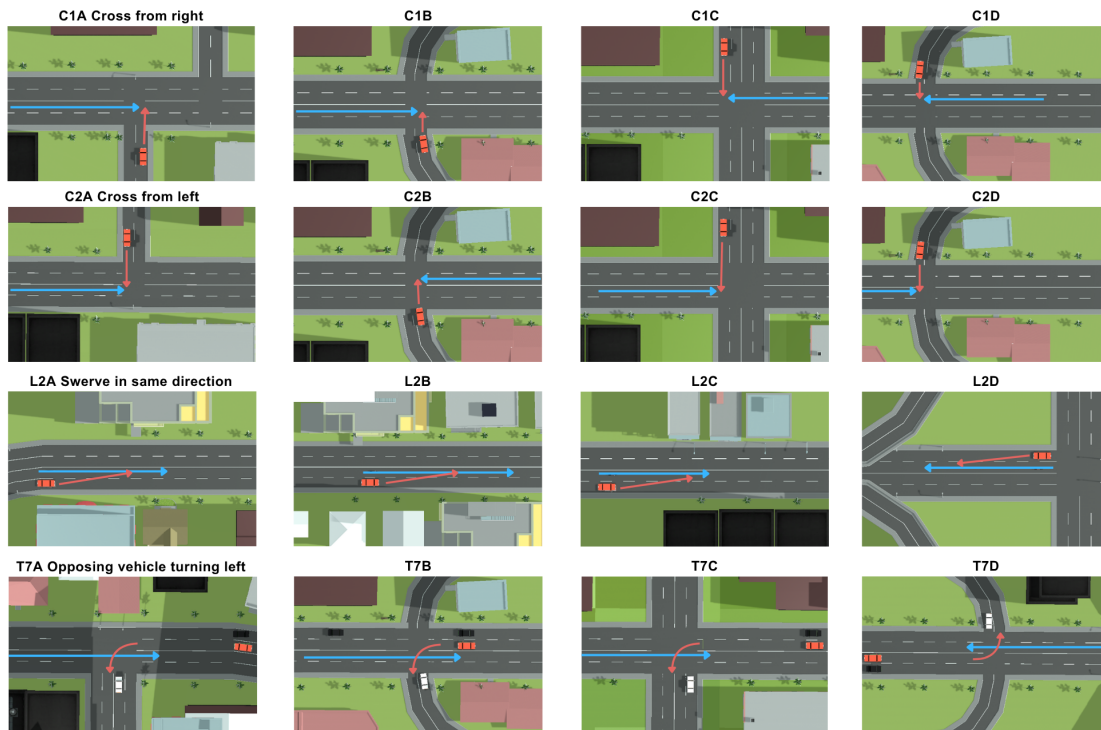


Fig. 3. Overview of the 16 hazard scenarios. Rows represent four common accident typologies (C1, C2, L2, T7), and columns (A–D) represent controlled variations in geometry and positioning. Rider trajectory is shown in blue, and conflicting hazard vehicle trajectory in red.

Three types of cues were given. Visual cues were displayed using two WS2812B LED strips integrated in the upper and lower visor of the helmet, located just inside peripheral vision. When triggered, a high-intensity red (R:255, G:0, B:0) warning was activated, consisting of five adjacent LEDs. The position of this block was dynamically updated based on the relative angle between the forward vector of the rider and the predicted collision point in the Unity environment, providing a clear spatial orientation. Auditory feedback was delivered as a series of spatialised, procedurally generated sine-wave tones. Using a dedicated audio synthesis script, an 800 Hz signal was generated with a duration of 250 ms per

pulse. These signals were mapped to the helmet’s 8Ω 1W speakers using a linear roll-off spatial blend (1.0f) to ensure that the sound appeared to originate from the direction of the specific hazard. To ensure high saliency and prevent perceptual adaptation, visual and auditory cues were delivered in a pulsing duty cycle of 300 ms (3.33 Hz) for as long as the hazard remained within the critical TTC threshold. In the multimodal condition, the LED pulses and auditory tones were synchronised to provide a unified cross-modal warning.

### 2.3 Procedure

Each experimental session consisted of four phases: an intake questionnaire, an acclimatisation phase, simulator trials, and a post-test questionnaire.

*Intake questionnaire.* At the beginning of the session, participants completed a digital intake questionnaire capturing demographic data (age, gender) and riding profile (annual mileage and frequency) (approximately 3–5 minutes). The questionnaire also established a baseline for technological readiness by measuring general trust in automation, preferences for warning modalities and prior experiences with near-miss traffic conflicts. Participants rated their initial expectations regarding the credibility of a helmet-integrated predictive system on a 5-point Likert scale.

*Acclimatisation phase.* Participants performed a 5-minute acclimatisation drive to familiarise themselves with the simulator controls and the different feedback modalities. This phase ensured that participants reached a steady-state comfort level with the interaction dynamics prior to data collection.

*Simulator trials.* The main experiment followed a within-subject design. Each participant completed 16 randomised trials as described in [subsection 2.2](#) above.

*Post-test questionnaire.* After the trials, the participants completed a post-test questionnaire (approximately 5–10 minutes). The questionnaire evaluated the MOTEX interface across four dimensions: (a) *Perceptual quality*: clarity of cues, realism of the simulation, and perceived timing (earliness) of alerts; (b) *Psychological impact*: situation awareness, cognitive workload, and trust in the accuracy of the system, measured using 5-point Likert scales; (c) *Behavioural change*: open-ended questions on how cues influenced response behaviour compared to unassisted riding; (d) *Feasibility and future adoption*: preferences for hardware integration (modular vs. built-in), expected price points, and perceived barriers to adoption. Open-ended responses were collected as part of the post-test questionnaire, allowing participants to elaborate on their experiences with the system in their own words. These responses focused on perceived usefulness, clarity, timing of feedback, and any experienced distraction or cognitive load. The questionnaire was completed immediately after the trials to capture fresh impressions. All responses were recorded digitally and included in anonymised form in the supplementary material.

### 2.4 Data Analysis

Reaction time (RT) and minimum time-to-collision (TTC) were calculated relative to the onset of the hazard warning, defined at a TTC threshold of  $\leq 2.0$  s. Reaction time was operationalised as the earliest meaningful rider response following cue onset ( $RT_{\text{primary}}$ ), defined as braking input or sustained steering action. Throttle-only responses were excluded because they did not constitute concrete evasive behaviour, as participants often switch between acceleration and engine braking within the simulator, thus switching between a high and low value of throttle position. Behavioural data were analysed using repeated-measures ANOVA to assess the effect of feedback modality. The C1C and all L2 variant scenario variants were excluded from the TTC-based analyses because their kinematic structure produced invalid TTC behaviour. In these scenarios, near-zero closing velocities resulted in non-monotonic or frozen TTC values, preventing meaningful interpretation of safety margins. These exclusions were applied uniformly before the analysis

and did not affect the reaction-time or reaction-strategy analyses. The quantitative data were analysed using a Friedman test with Bonferroni-corrected Wilcoxon post-hoc comparisons.

In addition to quantitative measures, qualitative data were collected through open-ended questionnaire responses. These responses were analysed using a thematic analysis approach. The initial codes were derived inductively from the data, focusing on recurring themes related to perceived usefulness, timing of feedback, clarity, and cognitive load. The responses were then grouped into higher-level themes to support the interpretation of the quantitative findings.

### 3 Results

#### 3.1 Reaction Time and Perceived Timing of Feedback

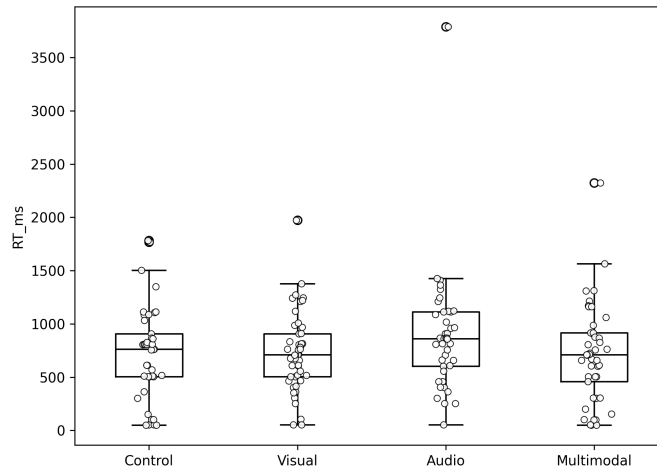


Fig. 4. Reaction time ( $RT_{primary}$ ) by feedback modality.

Data from 13 participants were included in the quantitative behavioural analysis. Across all feedback modalities, mean reaction times ranged from approximately 570 ms to 750 ms, with considerable variability within and between participants. The mean  $RT_{primary}$  values  $\pm$  SD were  $574 \pm 317$  ms for the visual condition,  $662 \pm 354$  ms for the audio condition,  $570 \pm 360$  ms for the multimodal condition, and  $747 \pm 445$  ms for the control condition. As shown in Figure 4, visual and multimodal conditions yielded numerically faster responses than audio and control conditions, while control trials showed the slowest overall responses. This trend was also visible at the scenario level, although the distributions in Figure 5 indicate substantial overlap between conditions and marked participant-specific variation. A repeated-measures ANOVA with feedback modality as a factor within the subject did not reveal a statistically significant main effect on  $RT_{primary}$  ( $F(2, 26) \approx 1.17$ ,  $p \approx 0.33$ ).

However, subjective data provide a more nuanced picture of how feedback was experienced. Although participants consistently reported that the system was clear and non-intrusive, its contribution to awareness and action preparation was more limited. A large majority of participants agreed that the feedback was clear within the simulated context (92.3%), and none reported cognitive overload, with 69.2% explicitly disagreeing that the alerts were overwhelming.

In contrast, perceived timing emerged as a key limitation: 69.2% of participants disagreed that alerts appeared early enough to take action, while only 30.8% reported positive evaluations. This aligns with qualitative feedback, where

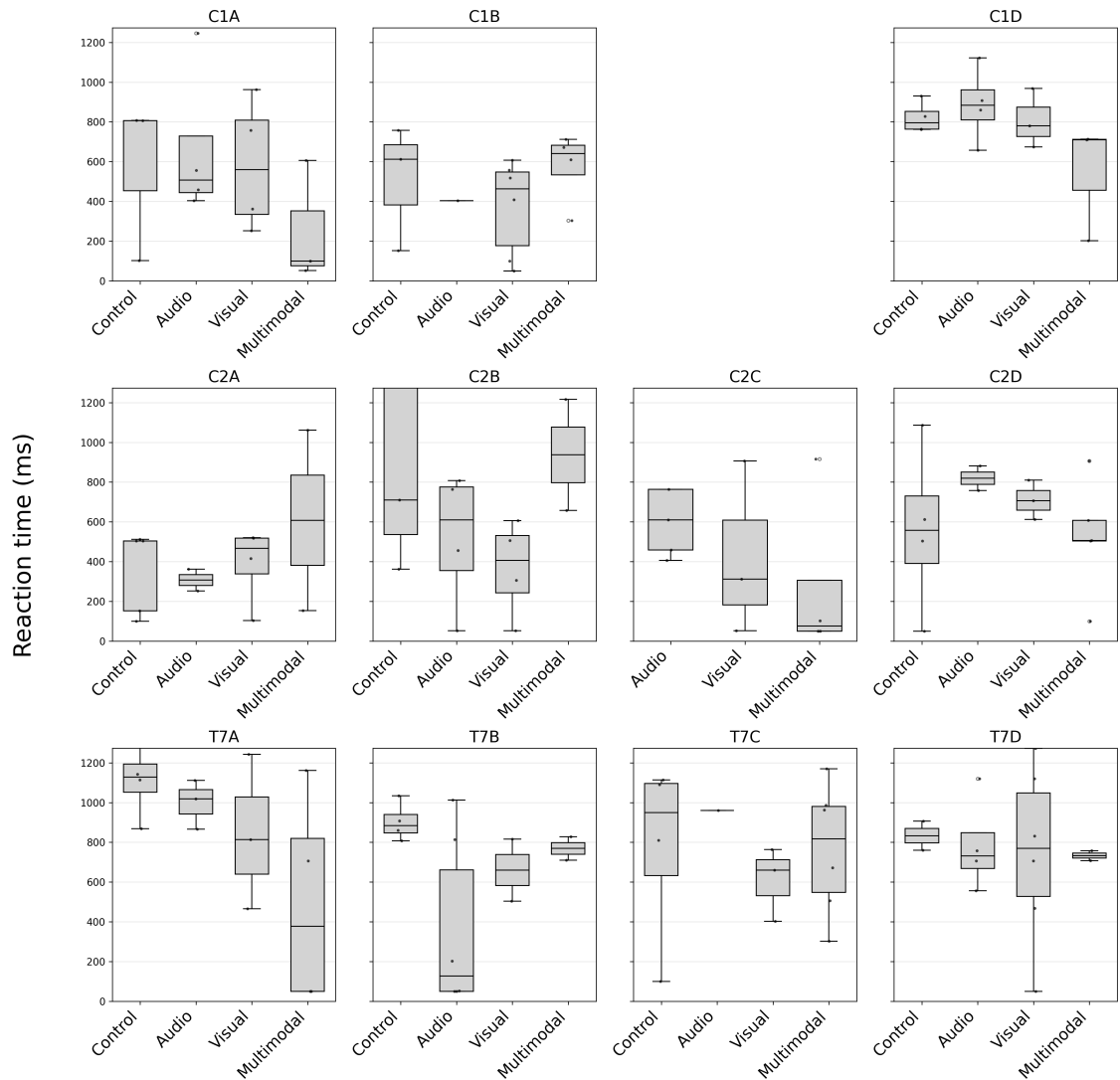


Fig. 5. Reaction time distributions by feedback modality across hazard scenarios.

several participants indicated that they had already visually detected the hazard before the cue was presented, describing the system as confirmatory rather than initiatory.

Perceived awareness followed a similar pattern. Although some participants reported increased awareness (23.1%), the majority of responses were neutral (61.5%), suggesting that the system did not introduce new information consistently, but rather reinforced existing perception.

Taken together, these findings help explain the behavioural results. Although feedback modalities did not produce statistically significant differences in reaction time or safety margins, visual and multimodal cues were associated with

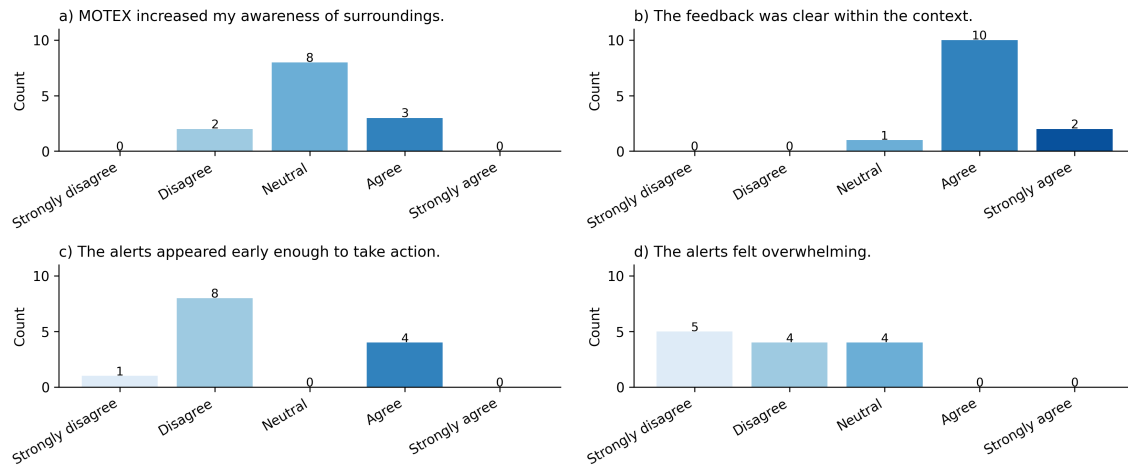


Fig. 6. Distribution of participant responses across four post-test questionnaire items ( $N = 13$ ), reflecting perceived awareness, clarity, timing, and cognitive load of the MOTEX feedback. Participants reported high perceived clarity (92.3% agreement) and low cognitive overload (69.2% disagreement). In contrast, perceived timing was predominantly negative (69.2% disagreement), indicating that alerts were often experienced as too late to support action. Perceived awareness showed a neutral-dominated distribution (61.5%), with fewer positive responses (23.1%), suggesting that the system was primarily experienced as confirmatory rather than anticipatory.

numerically faster responses. This suggests a modest supportive effect, likely limited by timing constraints and strong inter-individual variability. Exploratory inspection also indicated that the differences between participants were greater than the differences between the modalities, and no consistent relationship was observed between self-reported trust and measured reaction time. Exploratory inspection further showed that participant-level differences in RT were greater than modality-level differences, and no consistent relationship was observed between self-reported trust and measured reaction time.

### 3.2 Safety Margin and Perceived Control

The minimum TTC, which represents the smallest safety margin reached between the onset of the signal and the response of the rider, also showed modest numerical differences between conditions. The mean minimum TTC values  $\pm$  SD were  $1.31 \pm 0.40$  s for the multimodal condition,  $1.28 \pm 0.37$  s for the visual condition,  $1.21 \pm 0.38$  s for the audio condition, and  $1.14 \pm 0.36$  s for the control condition. Figure 7 shows that multimodal and visual feedback was associated with slightly larger safety margins than audio and control, and the scenario-level distributions in Figure 8 show the same general trend. However, these differences were not statistically significant: repeated-measures ANOVA did not show a main effect of the feedback modality on minimum TTC ( $F(2, 26) \approx 0.90$ ,  $p \approx 0.42$ ). Thus, as with reaction time, the behavioural data indicate directional but non-significant advantages for multimodal and visual cues.

Perceptual data provide an important complement to this pattern. In the post-test questionnaire, 60% of the participants agreed or strongly agreed that they trusted the system to warn them accurately and 60% rated the warnings as reliable. In addition, 70% agreed that traffic situations felt realistic compared to their real-world riding experience. Participants often described the feedback as confirming their own perception of an emerging hazard rather than changing what they physically did. Taken together, these findings suggest that the system may have supported a greater sense of control

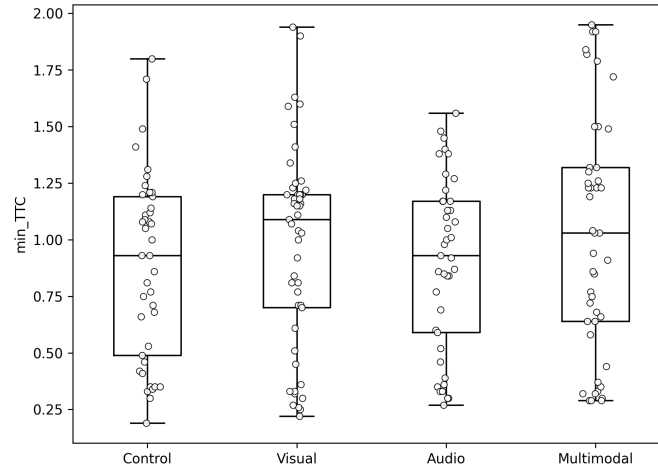


Fig. 7. Minimum time-to-collision by feedback modality.

and hazard confirmation without substantially changing the timing of evasive behaviour. This again points to the role for MOTEX as an awareness-support tool rather than as a strong determinant of rider response execution.

### 3.3 Reaction Strategy and Behavioural Stability

Across all feedback modalities, participants responded predominantly by braking, while steering was used in a substantial minority of the trials. Braking remained the dominant strategy in all conditions, with approximate proportions of 68% braking and 32% steering in both visual and multimodal conditions, and 64% braking and 36% steering in the audio condition.

Statistical analysis did not show an association between feedback mode and reaction strategy (chi-square test,  $p \approx 0.91$ ). The questionnaire responses were consistent with this result: 80% of the respondents indicated that the alerts did not change the way they reacted to hazards. Rather than prompting different manoeuvres, the feedback appears to have supported riders' existing strategies. This is notable in light of the numerical trends reported above because it suggests that any potential benefit of the cues operated primarily through awareness and preparation rather than through changes in the chosen evasive action.

### 3.4 Cognitive Load, Distraction, and Response Consistency

To examine the cognitive load, distraction, and response consistency, we compared the variability of  $RT_{primary}$  across modalities. Numerically, the reaction-time variability was highest in the multimodal condition and lowest in the audio and visual conditions. However, a Levene-type test based on median-centred values did not reveal statistically significant differences in variability between modalities ( $p \approx 0.34$ ). Thus, the feedback mode did not measurably affect the consistency of the response at the group level.

Subjective workload ratings also indicated that participants rarely experienced feedback as distracting or cognitively demanding. In the post-test questionnaire, 77.8% of the respondents disagreed or strongly disagreed that the alerts felt overwhelming, while the remaining participants reported neutral experiences; no participant indicated that the

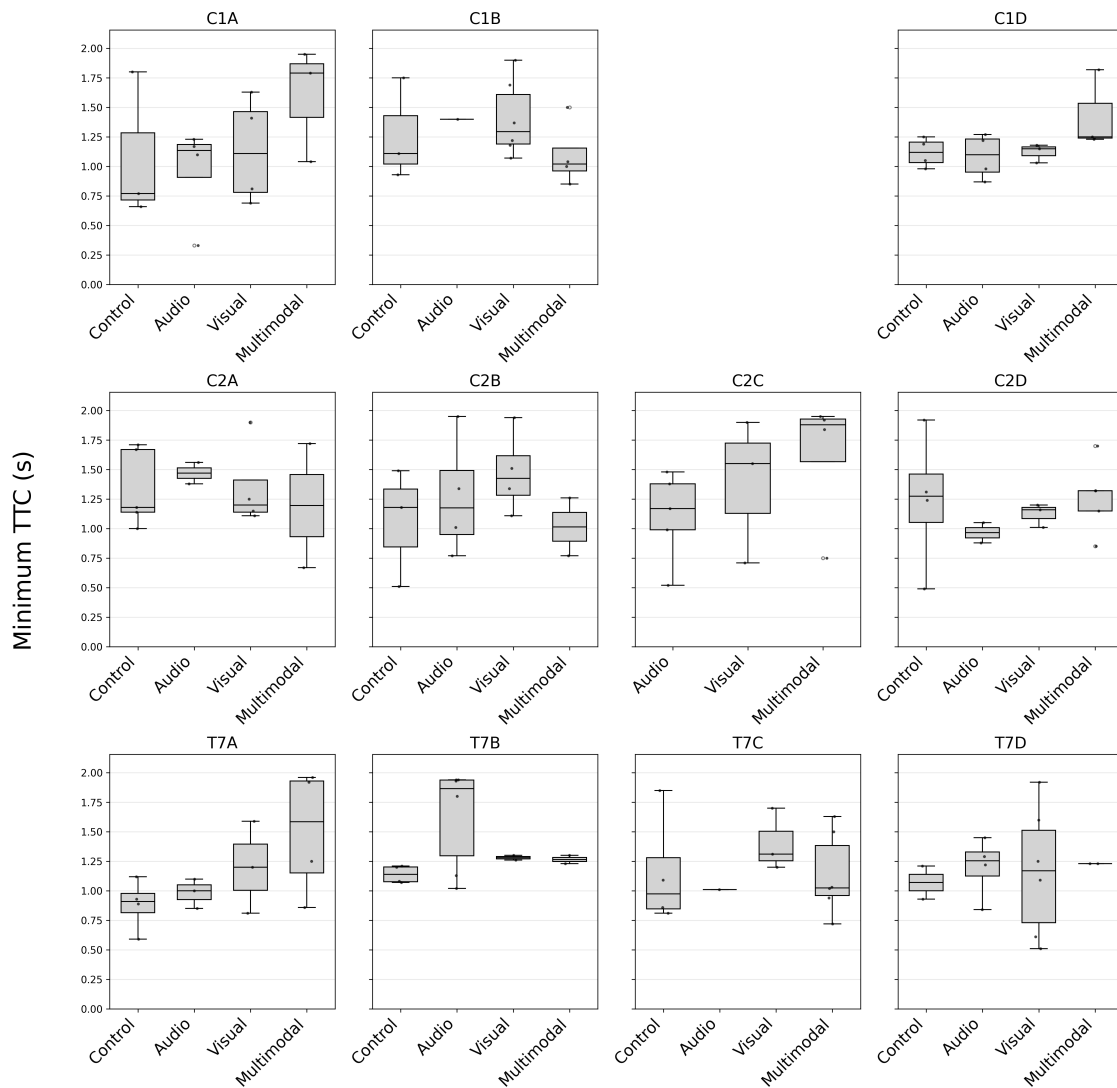


Fig. 8. Minimum time-to-collision distributions by feedback modality across scenarios.

system caused cognitive overload. Riders frequently reported that the peripheral nature of the cues allowed them to maintain focus on the riding task without disrupting scanning or control behaviour. When considered together with the earlier findings, this final pattern helps clarify the overall result profile of the study: the feedback modality did not produce statistically significant differences in reaction time, minimum TTC, reaction strategy, or response variability, yet multimodal and visual feedback consistently showed numerically faster responses and higher safety margins, while subjective responses indicated increased awareness (70%), low overload (77.8%) and moderate trust in system precision (60%). In general, rider-specific factors appeared to account for more variance than modality alone, suggesting that

the main contribution of the system in its current form was to support awareness and spatial confirmation without imposing additional cognitive burden.

#### 4 Discussion

This study evaluated whether a helmet-integrated multimodal feedback system can support anticipatory hazard awareness for motorcyclists in time-critical urban scenarios. The results provide a nuanced understanding of how predictive feedback influences rider behaviour beyond simple reaction speed.

A central finding is the mismatch between objective behavioural (**RQ1**) and subjective perception (**RQ2**) metrics. Although repeated-measures ANOVA did not reveal statistically significant differences in RT ( $p = 0.33$ ) or TTC ( $p = 0.42$ ), 70% of participants reported that the MOTEX system made them feel significantly more aware. This pattern is consistent with broader findings in the driver assistance literature, where subjective confidence and perceived usefulness frequently diverge from objectively measurable performance gains, particularly when the intervention is subtle and advisory in nature [1, 28]. This divergence can be interpreted through the lens of DSA theory [31]: rather than directly altering the physical response of the rider, MOTEX contributed to the broader sociotechnical system by externalising the hazard-relevant information that the rider could integrate into their own awareness state. From a DSA perspective, the HMI functioned as an additional node in the awareness network, sharing compatible SA elements with the rider without prescribing a specific motor response. This is consistent with participant reports that described feedback as confirmatory rather than directive and explains why perceived situational awareness increased despite the absence of measurable changes in reaction time or safety margin. Riders often possess an intuitive sense of emerging danger and the HMI functions as a secondary validation layer that strengthens the rider's own perception [10], closing the gap between what the rider senses and what the system has already computed.

Based on behavioural results and qualitative feedback, we propose four design principles for proactive rider assistance (**RQ3**). First, advisory cues should take precedence over prescriptive ones: riders valued feedback that informed their scanning patterns rather than instructing specific manoeuvres, which is consistent with the principle that preserving rider autonomy is critical for both user acceptance and the ethical allocation of liability in semi-automated systems [29, 34]. Second, peripheral minimalism should be maintained: the high disagreement with feeling overwhelmed (77.8%) suggests that peripheral RGB LEDs and spatial audio can be integrated without inducing cognitive bottlenecks, provided that they remain abstract and brief [37]. This finding aligns with Multiple Resource Theory, which predicts that cross-modal cues presented at the periphery of the primary task impose minimal additional load [36]. Third, multimodal robustness offers a redundancy advantage: while multimodal cues did not statistically outperform visual-only cues, their value lies in sensory redundancy, as in varied environmental conditions such as high wind noise or intense glare, the secondary channel ensures that the hazard cue is perceived [19, 33]. Fourth, timing calibration is essential for shifting the system from reactive to genuinely proactive: the mixed feedback on the 2.0 s TTC trigger suggests that the alert threshold should be moved closer to 3.0–4.0 s TTC, which would relocate the HMI intervention from the emergency response window into a search-and-identify support window, more in line with the comprehension and projection levels of Endsley's SA model [10, 20].

By bridging the gap between field-survey requirements gathered at EICMA and simulator validation, this study demonstrated that a decoupled HMI can enhance a rider's perceived situational awareness without disrupting natural control strategies. Although the MOTEX system did not yield decisive gains in reaction time within the tested 2.0 s window, it established a high degree of rider trust (60%) and a low cognitive workload (77.8% non-overwhelmed). These findings suggest that the future of motorcycle safety lies not in replacing the judgement of the rider with automation,

but in supporting it through subtle, directional, and multimodal spatial confirmation [28, 29]. This project lays the groundwork for next-generation safety systems that are meaningfully integrated into the rider’s primary equipment rather than relegated to the dashboard.

#### 4.1 Limitations and Future Work

The absence of significant behavioural effects may be attributed to high inter-individual variability and the complexity of the simulator task. By requiring both steering and braking responses, the study prioritised ecological validity over isolated reaction speed measurement. The sample size ( $N = 13$ ) further limits the statistical power, and replication with a larger cohort is necessary before generalising these findings [22]. Future work should involve longitudinal studies to investigate behavioural adaptation—ensuring that riders do not begin to wait for the system before scanning for hazards, a known risk in automation-assisted driving contexts [20, 29]—and testing in dynamic physical environments to account for vestibular and proprioceptive forces that are absent in simulator conditions but are central to real-world motorcycling [6]. A dedicated on-road validation study may be a natural next step in assessing whether the awareness benefits observed in the simulator transfer to real traffic. The alert timing threshold with TTC of 2.0 s, identified as too late by 40% of participants, should be systematically varied in follow-up work to establish an optimal proactive window. Based on current findings, a threshold in the range with TTC of 3.0–4.0 s is a promising candidate [10, 20]. Given that rider-specific factors consistently accounted for more variance than modality alone, future designs should explore adaptive or personalised alert profiles that account for individual differences in hazard perception and riding style. multimodal robustness/redundancy should also be empirically tested under ecologically valid noise and glare conditions, as the present study was conducted in a controlled acoustic and lighting environment. Finally, future work should investigate the transition from the current prototype towards a manufacturable modular retrofit.

#### 5 Supplementary Material

In line with current open science practices and recommendations for transparency in automotive user research [9], the authors openly provide these research artefacts to support reproducibility, collaboration and further advancements in the field. The simulator and analysis code, the anonymised data and the materials used in the experiment are available at [https://www.dropbox.com/scl/fo/z1nmh1dqsy6z1yidahh1/AJD5BaZEzN\\_XaQqV2JPXL4U?rlkey=k7d8zl1kx9holfpv051fwlve8](https://www.dropbox.com/scl/fo/z1nmh1dqsy6z1yidahh1/AJD5BaZEzN_XaQqV2JPXL4U?rlkey=k7d8zl1kx9holfpv051fwlve8). The maintained version of the code is available at <https://github.com/T-vH/motex>.

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