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Mobile Platform for Integrated Multimodal Data Capture in Immersive First Responder Training and Decision Support Research

Martin Pszeida[1], Wolfgang Weiss[1], Michael Schneeberger[1], Jochen A. Mosbacher[1], Clemens Könczöl[2], Deborah Huber[2], Alexander Elser[3], Manfred Pollheimer-Stadlober[2], Sandra Pichler[4], Jasmina Schmidt[4], Klaus Tschabuschnig[5], Josef Rampitsch[5], Georg Schwarzott[6], Hannes Kern[7], Dietrich Albert[2], Bettina Kubicek[2], Marie Ottilie Frenkel[3], and Lucas Paletta[1]

[1]JOANNEUM RESEARCH, DIGITAL - Institute for Digital Technologies, Austria
[2]University of Graz, Department of Psychology, Austria
[3]Furtwangen University, Faculty Health, Medical, and Life Sciences, Germany
[4]Disaster Competence Network, Austria
[5]State Firefighting Academy Carinthia, Austria
[6]Professional Fire Department Vienna, Austria
[7]IRIS - Industrial Risk and Safety Solutions e.U., Austria

ABSTRACT

Immersive VR training enables first-responder academies to rehearse hazardous incidents safely and repeatedly. Yet objective assessment of decision-making under operational stress remains challenging when physiology, eye tracking and contextual video are recorded by heterogeneous systems with inconsistent timestamps. This paper presents a mobile platform for integrated multimodal data capture in immersive first-responder training. The system combines a "Meta Quest 3" head-mounted display (HMD), "Pupil Labs Neon" eye tracking, BIOPAC "MP160/BioNomadix physiology", "Polar H10" ECG, external video, first-person screen recording and Study Recording Software for session control, status monitoring and standardized data management. A pilot deployment at the State Firefighting Academy Carinthia demonstrated synchronized recording of multiple-data streams without disrupting training operations. The data acquisition workflow aligns gaze behaviour, pupil diameter, blink rate, ECG and heart-rate measures, electrodermal activity (EDA), video recordings, and scenario events within a common temporal framework. Video-sequence analytics are used to segment virtual reality (VR) missions into operational phases, creating expert-review clips and anchors for multimodal feature extraction. The primary contribution is a deployable human-factors research platform that integrates immersive training, psychophysiological state monitoring, synchronized multimodal data capture, and structured debriefing into a coherent workflow, thereby providing a methodological foundation for reproducible training evaluation, evidence-based performance assessment, and future adaptive decision-support systems for first-responder operations.

Keywords: Immersive VR, First responders, Decision-making, Eye tracking, Pupillometry, Bio-signals, Video sequence analytics, Multimodal data synchronization, Human factors, Debriefing.

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INTRODUCTION

Firefighting and rescue operations require fast decisions under uncertainty, time pressure, incomplete information and high consequence conditions (Klein et al., 2010; Wheeler et al., 2021). These situations are also shaped by physiological arousal, stress and cognitive load, which can influence situational awareness, decision making and operational performance (Oliveira et al., 2024; Wheeler et al., 2021). Training environments therefore need to reproduce not only the visual and procedural elements of an incident, but also the cognitive demands and stress-related dynamics that shape performance in realistic emergency contexts (Oliveira et al., 2024; Wheeler et al., 2024). Immersive virtual reality (VR) is a promising medium because it can expose trainees to rare, complex or dangerous situations without putting people, equipment or infrastructure at risk (Engelbrecht et al., 2019; Berthiaume et al., 2024). It also allows instructors to repeat scenarios, vary task demands and compare trainee performance across sessions under controlled and ecologically valid conditions (Oliveira et al., 2024; Wheeler et al., 2024).

However, the scientific value of immersive training depends on more than the VR scene itself. Trainers and researchers need reliable evidence about when relevant decisions occur, which cues are inspected, whether the trainee shows physiological activation, and how these signals relate to mission events. In practice, these data are often distributed across the VR system, an eye tracker, a biosignal recorder, local video files and handwritten trainer notes. This fragmentation makes post-hoc analysis slow, reduces trust in timestamps and limits the effectiveness of structured debriefing.

The EMERDEC mobile platform addresses this gap by integrating multimodal data streams from eye tracking, psychophysiological monitoring, scenario video, and event-based segmentation into a unified mobile data-capture workflow for operational training environments. The platform was developed within a research project investigating the fundamentals of decision-making processes in primary emergency response and provides a methodological basis for reproducible human-factors studies, evidence-based debriefing, and future decision-support systems (Kern et al., in press; Elser et al., in press; Koenczoel et al., in press).

The goal of this mobile data-capture system is not to replace instructors or to automate performance assessment. Instead, the platform creates synchronized evidence that can support structured expert ratings, explainable debriefing and later development of adaptive assistance. Figure 1 illustrates the operational context of the EMERDEC platform, where trainees engage in an immersive fire-service scenario while an operator monitors the session.

RELATED WORK AND CURRENT STATE OF RESEARCH

Immersive VR has been discussed as a training and research tool for emergency response, disaster medicine and safety-critical education because it combines ecological cues with controllability and repeatability. Reviews of VR head-mounted displays emphasize benefits for spatial learning and experiential training, while also noting the need for carefully designed learning objectives, usability checks and outcome measures (Jensen and Konradsen, 2018; Radianti et al., 2020). In disaster medicine and first-responder settings, VR has been used for triage, mass-casualty response and hazardous incident rehearsal (Farra et al., 2013; Paletta et al., 2022; Brown et al., 2023; Kman et al., 2023).

Figure 1: Immersive first-responder training setup: (a) decision-maker wearing a Meta Quest 3 headset in front of the projected fire-service scenario; (b) VR trainee and operator workstation in a training room at the State Firefighting Academy Carinthia.

For firefighters, the value of VR depends on whether the virtual environment creates sufficient perceptual and behavioural equivalence to real training or operations. Recent work on virtual firefighting scenarios therefore evaluates presence, perceived stress, fatigue, knowledge transfer and physiological indicators rather than relying only on subjective acceptance (Reim et al., 2022; Narciso et al., 2024; Wrzus et al., 2024). This aligns with a human-factors view: decision quality in an incident is shaped by attention allocation, workload, situational awareness, physiological arousal and interaction constraints.

To assess these factors, different measures can be employed. Eye tracking provides a direct measurement channel for visual attention and visual-cognitive behaviour. Fixations, saccades, gaze transitions, blink rate and pupil diameter can help to describe scanning strategies and task engagement. Cognitive pupillometry has a long tradition as an indicator of processing load (Beatty, 1982), but field use requires careful control of luminance, movement and device quality. In parallel, heart-rate variability and electrodermal activity are common psychophysiological measures for autonomic regulation and stress-related arousal (Benedek and Kaernbach, 2010; Shaffer and Ginsberg, 2017; Schneeberger et al., 2022; Wrzus et al., 2024).

Despite these advances, most training studies still collect behavioural, physiological and contextual data using separate systems, making reliable temporal synchronization and integrated analysis difficult. Multimodal experiments often combine various devices, deployed as distributed systems with individual clocks, sampling rates, buffers and transmission paths. Frameworks such as the Lab Streaming Layer illustrate how per-sample timestamps and clock offset estimation can support synchronized neurophysiological and behavioural recording (Kothe et al., 2025).

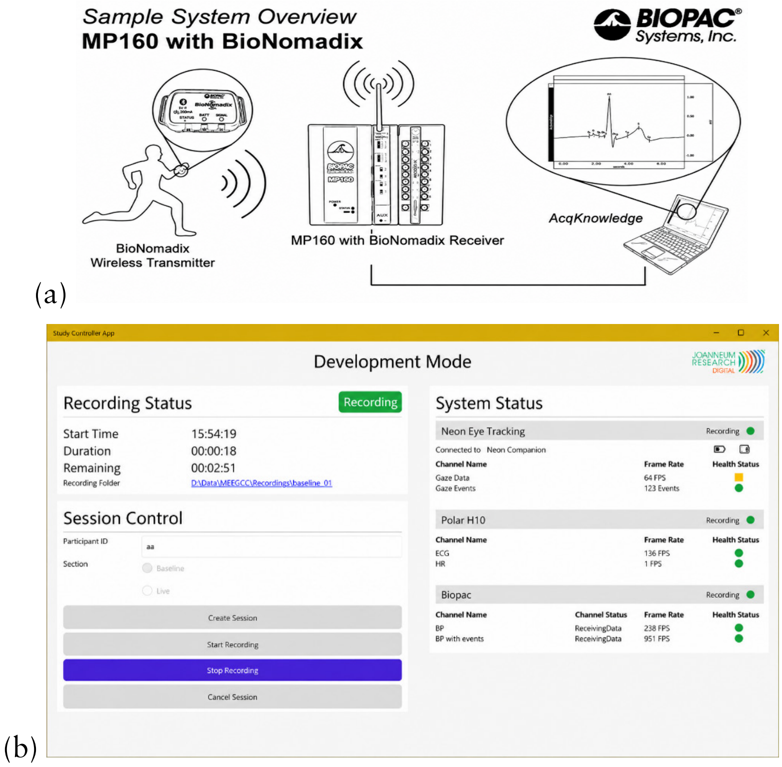
Building on these synchronization principles, the EMERDEC platform provides an operationally deployable framework that integrates eye tracking, psychophysiological monitoring, video capture and event-based analysis within a single workflow for immersive first-responder training.

SYSTEM ARCHITECTURE

The architecture consists of four functional layers: (1) immersive scenario execution, (2) wearable sensing, (3) study control, and (4) synchronized recording and data management. Together, these layers provide a unified workflow for multimodal data acquisition in operational VR training environments.

The immersive layer uses a Meta Quest 3 headset connected via cable to the scenario workstation for stable streaming and screen capture. A mounted Pupil Labs Neon module captures high-frequency eye videos and gaze-related features. Physiological sensing is implemented through a BIOPAC MP160 with BioNomadix wireless transmitters and a Polar H10 chest strap as redundant ECG source. This redundancy is useful because it allows cross-checking of heart-rate-derived measures and helps identify signal dropouts during movement.

The Study Recording Software (Figure 2) provides a unified operator interface for participant management, baseline acquisition, recording control, device-status monitoring, and automated session packaging. This reduces operator workload and minimizes synchronization errors that commonly occur when multiple vendor-specific tools must be managed independently.



Recording Status

Start Time 15:54:19
Duration 00:00:18
Remaining 00:02:51
Recording Folder D:\Data\MEEGCC\Recordings\baseline_01

Session Control

Participant ID aa
Section ○ Baseline ○ Live

System Status

Neon Eye Tracking — Recording ●

Connected to Neon Companion

Channel Name	Frame Rate	Health Status
Gaze Data	64 FPS	■
Gaze Events	123 Events	●

Polar H10 — Recording ●

Channel Name	Frame Rate	Health Status
ECG	136 FPS	●
HR	1 FPS	●

Biopac — Recording ●

Channel Name	Channel Status	Frame Rate	Health Status
BP	ReceivingData	238 FPS	●
BP with events	ReceivingData	951 FPS	●

Figure 2: Biosignal and control components: (a) BIOPAC MP160/BioNomadix wireless measurement setup; (b) custom Study Recording Software showing recording status, session control and live connection health for Neon eye tracking, Polar H10 and BIOPAC streams.

This design reduces the number of independent operator actions that would otherwise be needed across several vendor tools. It also enables a standardized baseline before the scenario and consistent data packaging after the scenario.

The architecture includes two complementary video channels. First, an external camera records the participant, controllers, room context and operator actions. Second, the first-person VR perspective is recorded from the scenario computer using screen-recording software and an embedded on-screen timestamp. Together, these channels make it possible to what the trainee perceived, how the trainee responded physiologically, and what the operator observed. The external view is essential for behavioural annotation and quality control, while the ego perspective provides direct scenario context and event anchors.

A key design objective is robust temporal synchronization across heterogeneous devices. To achieve this, the platform combines timestamped sensor streams, clock-offset logging, controller-generated event markers, and visual anchors embedded in first-person recordings. This multi-layer synchronization strategy increases resilience against field-related disturbances such as wireless latency, temporary signal loss, asynchronous buffering, or delayed video encoding.

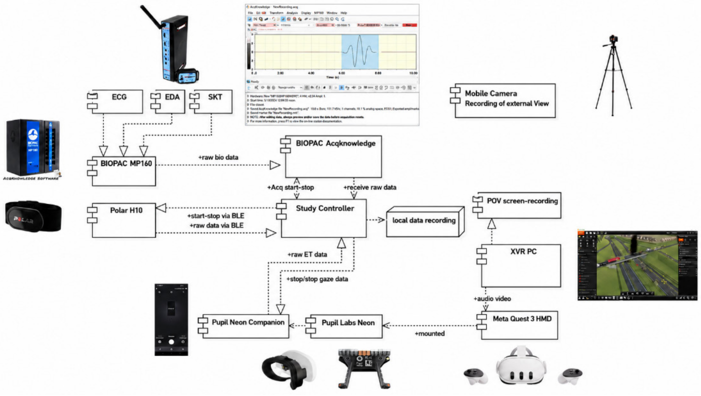


Figure 3: System architecture of the integrated multimodal data recording system, connecting BIOPAC/AcqKnowledge, Polar H10, Pupil Labs Neon Companion, Meta Quest 3, XVR scenario PC, screen recording and external camera recording through JR recording software and local per-user data storage.

Figure 3 shows the resulting modular architecture. The biosignal data is captured by ECG, electrodermal activity and skin temperature through BIOPAC/AcqKnowledge, while the Polar H10 adds an independent ECG stream via Bluetooth Low Energy. The eye-tracking system uses the Neon Companion mobile app and a mounted Neon from Pupil Labs[1] module inside the headset. The scenario side includes the XVR PC, the Meta Quest 3 headset, first-person screen recording and external camera recording.

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[1] https://pupil-labs.com/

The Study Controller recording software acts as the integration layer that starts, stops and stores the session data in a common folder structure.

The synchronized data package supports several analysis levels. At the low level, raw sensor streams and videos are preserved for audit and re-analysis. At the feature level, the platform extracts blink rate, pupil diameter, gaze validity, saccadic activity, heart rate, heart rate variability and EDA measures in windows around scenario events. At the interpretation level, the synchronized timeline enables trainer-defined event ratings, for example whether the trainee noticed a hazard, delayed a critical decision or showed signs of overload during the approach to the incident scene.

PILOT EVALUATION OF THE SYNCHRONIZED DATA CAPTURE WORKFLOW

A field deployment for a pilot study was conducted in a firefighter VR training setting. The pilot deployment was designed to evaluate whether multimodal data streams could be recorded, synchronized, and segmented under realistic training conditions without disrupting operational training procedures.

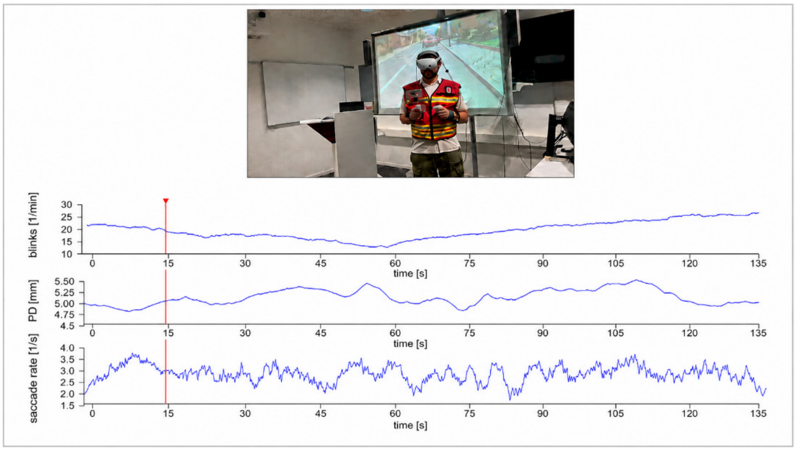

Figure 4: Example of synchronized video and numerical signal visualization. The upper panel shows the VR trainee in the training room; aligned time-series below show blink rate, pupil diameter (PD) and saccadic activity. A red marker indicates individual task duration with numerical biosignal data that are synchronized with the presented video frame.

Figure 4 illustrates an example of synchronized video and numerical signal visualization. The upper panel shows the VR trainee in the training room and provides the behavioural and scenario context for the displayed moment. The aligned time-series below show blink rate, pupil diameter (PD) and saccadic activity as synchronized numerical biosignal data. The red marker indicates the individual task duration and links the presented video frame to the corresponding signal values. This representation supports post-hoc inspection of how observable training behaviour relates to oculomotor and pupillometric responses within the same synchronized analysis window.

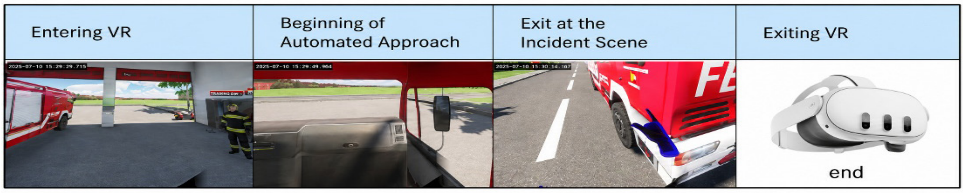

Figure 5: Video sequence analytics output. Four labelled segments are extracted from the VR mission: entry into VR, beginning of automated approach, exit at the incident scene and exit from VR. Labels become temporal anchors for synchronized feature extraction and expert-review clips.

Table 1: Video-sequence analytics output and analytical use.

Segment	Operational Meaning	Use in Multimodal Analysis
Entry into VR	Trainee enters the immersive environment and scenario context becomes visible.	Defines the start of scenario exposure and separates baseline from VR phase.
Automated approach begins	Vehicle movement starts and the trainee receives dynamic visual information.	Supports workload and attention analysis during transition from preparation to incident approach.
Exit at incident scene	Trainee leaves the vehicle and the operational task becomes action-oriented.	Marks a decision-critical interval for expert review and gaze/ physiology windowing.
Command to enter building	Trainee has finished exploration of incidence site and gives command for squad to enter the building.	Marks a decision-critical interval for expert review and gaze/ physiology windowing.
Squad signals status	Trainee receives response from squad inside the building about the progress of efforts & status of squad	Marks a decision-critical interval for expert review and gaze/ physiology windowing.
Squad signals accident	Trainee receives response from squad that a member of their team has issue with oxygen and needs assistance	Marks a decision-critical interval for expert review and gaze/ physiology windowing.
Exit from VR	Training scenario ends and headset use stops.	Defines endpoint for recovery analysis and post-scenario debriefing alignment.

The video-sequence analytics module transforms continuous VR recordings into structured event timelines. Each identified anchor defines a reproducible temporal window that can be linked directly to gaze behaviour, physiological responses, and expert assessments (Figure 5; Table 1). The currently implemented anchors identify entry into VR, beginning of automated approach, exit at the incident scene and exit from VR. The same mechanism can be extended with expert-defined anchors such as dispatch, hazard recognition, arrival, first report, first command, victim contact or scenario termination. These segments create standardized video-clips for re-analyses such as expert ratings and define reproducible windows for physiology and gaze analysis.

Three practical findings emerged from the pilot's deployment. First, the centralized session control makes multi-device recording feasible for a single operator with sensor health, recording state and session control being visible in one window. Second, the combination of first-person and external video supports both scenario-based annotation and behavioural quality control. Third, event-based video segmentation substantially reduces review effort by transforming long recordings into standardized analysis segments that can be reviewed by trainers and aligned with numerical signals (HR, HRV, eye-tracking signals, see Figure 4). This is essential for scaling from anecdotal debriefing toward quantitative evidence about attention, stress and decision-making.

The result should be interpreted as a proof of technical integration as an enabler for human-factors validation, to capture temporal synchronized data streams from distributed sensor systems. The pilot study was not designed to evaluate decision quality or develop predictive classifiers. Instead, its purpose was to validate the technical infrastructure required for future human-factors research. The principal contribution is the establishment of a reproducible multimodal data infrastructure.: Each session generates a standardized package containing synchronized sensor recordings, video streams, baseline measurements, event markers, and analysis-ready segments. Such consistency is a prerequisite for future investigations of how gaze behaviour, physiological responses, and training outcomes relate to decision quality under operational stress.

DISCUSSION AND OUTLOOK

The proposed platform supports a transition from immersive training environments that primarily provide experiential learning to training environments that also enable systematic human-factors assessment. It allows instructors and researchers to ask not only whether a trainee completed a task, but also how attention, physiological activation and scenario events unfolded over time. This is particularly relevant for first-responder decision-making, where errors often emerge from delayed cue detection, narrowed attention, stress-related overload or poor timing rather than from lack of procedural knowledge alone. Previous VR-based training research has likewise highlighted the importance of understanding attentional and psychophysiological mechanisms underlying operational decision-making under stress (Voigt & Frenkel, 2023; Frenkel & Strahler, 2025).

Future work will focus on three directions. The first is automated feature extraction from synchronized exports, including gaze validity, fixation structure, blink rate, pupil dynamics, heart-rate variability and EDA responses. The second is a trainer-oriented debriefing interfaces that links video clips, physiological summaries and event notes without exposing raw technical complexity. The third is validation against expert assessments and training outcomes to determine which multimodal indicators are robust enough for decision support or adaptive training. Beyond these, the platform can also be extended with speech, location, inertial motion or team-level communication features. As the platform evolves toward larger-scale deployment, ethical and privacy considerations become increasingly important because eye-tracking recordings, video data, and physiological measurements constitute sensitive personal information.

Publication or sharing of identifiable images requires appropriate consent, and research datasets should use pseudonymous identifiers, secure storage, and restricted access. In operational use, the platform should remain a decision-support and debriefing tool; it should not replace instructor judgement or impose automated performance scores without validated evidence and transparent interpretation. In conclusion, the EMERDEC mobile platform demonstrates a practical architecture for synchronized multimodal recording in immersive first-responder training.

By combining immersive VR, eye tracking, psychophysiological sensing, dual video capture, and video-sequence analytics within a synchronized workflow, the platform contributes to three core objectives. First, it establishes a reproducible methodological foundation for repeated and comparable data capture across trainees, scenarios, and sessions. Second, it enables human-factors research by linking observable behaviour with gaze, pupillometric, and physiological indicators of workload and stress. Third, it provides the basis for future decision-support systems that use synchronized multimodal evidence to support debriefing, performance assessment, and adaptive emergency-response training

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