ADVANCED MIXED REALITY TRAINING FOR FIRST RESPONDERS IN HURRICANE SCENARIOS

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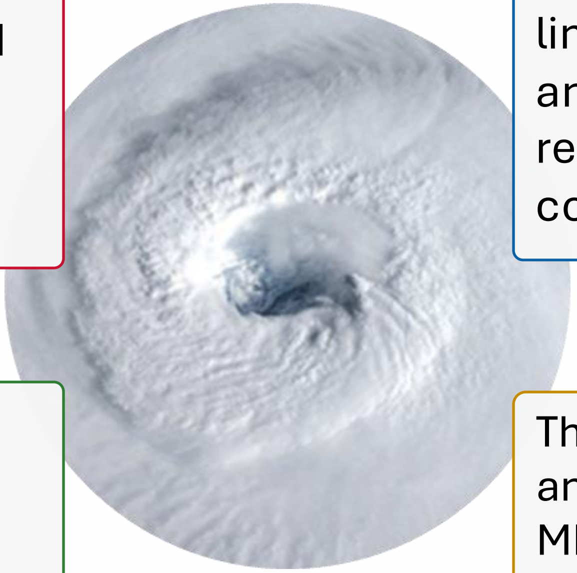
Introduction

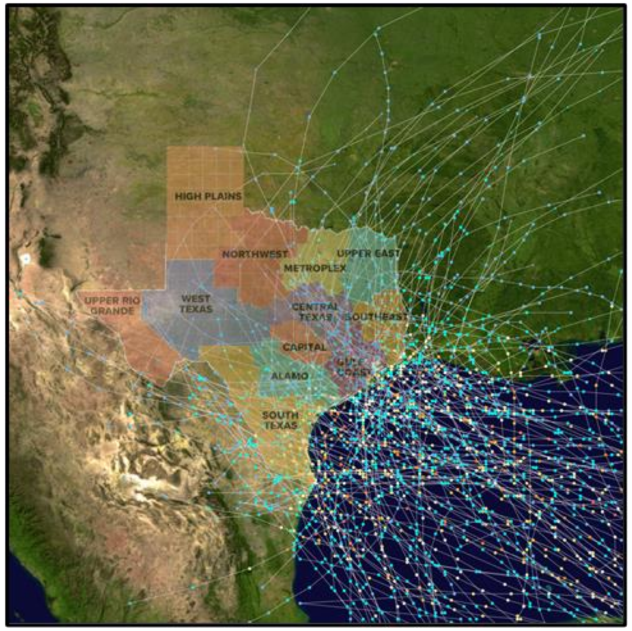
Hurricanes expose first responders to flooding, reduced visibility, debris, and unstable conditions.



Traditional training is often expensive, limited in realism, and difficult to repeat consistently.

Mixed reality can safely simulate hazard-rich environments in a controlled and scalable way.

This study develops and evaluates an MR flood training system for first responder preparation



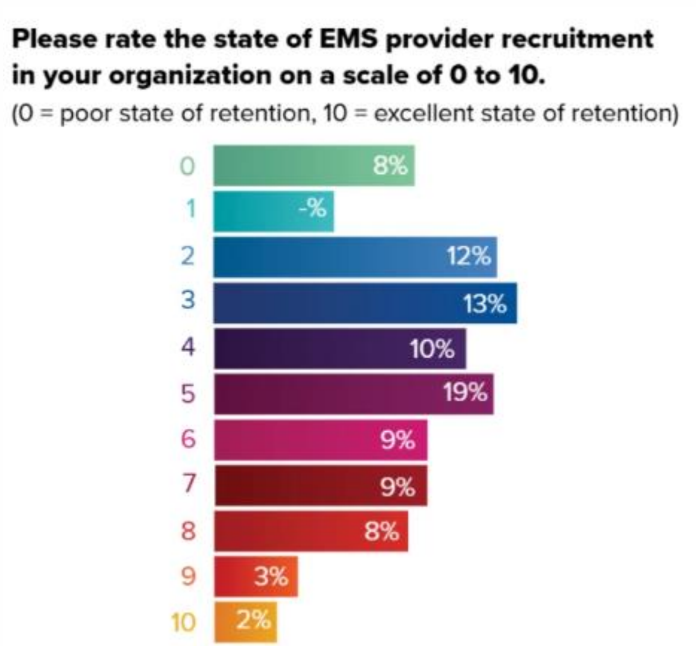
Southeast Texas is highly vulnerable to hurricanes

Introduction (Problem Statement)

Traditional training methods have limited realism, making it difficult to safely recreate the pressure and environmental complexity of actual disaster conditions.

Safety Risk: Fire/trauma/hazmat drills can pose danger to participants.
High Cost: Realistic Setups require time, space, and resources.
Repeatability & feedback: Hard to replicate conditions or assess performance.

Current US Workforce Statistics



nearly **60% of EMS agencies report insufficient staffing** to meet 911 demand, showing that workforce shortages remain a national operational problem.

national EMS reporting has shown turnover around **36% for full-time EMTs** and **27% for full-time paramedics**, with **more than one-third of new hires leaving within the first year**.

With about **19,000 annual EMT/paramedic openings** and hiring costs averaging **about $5,475 per hire**, agencies need training methods that are efficient, repeatable, and scalable.

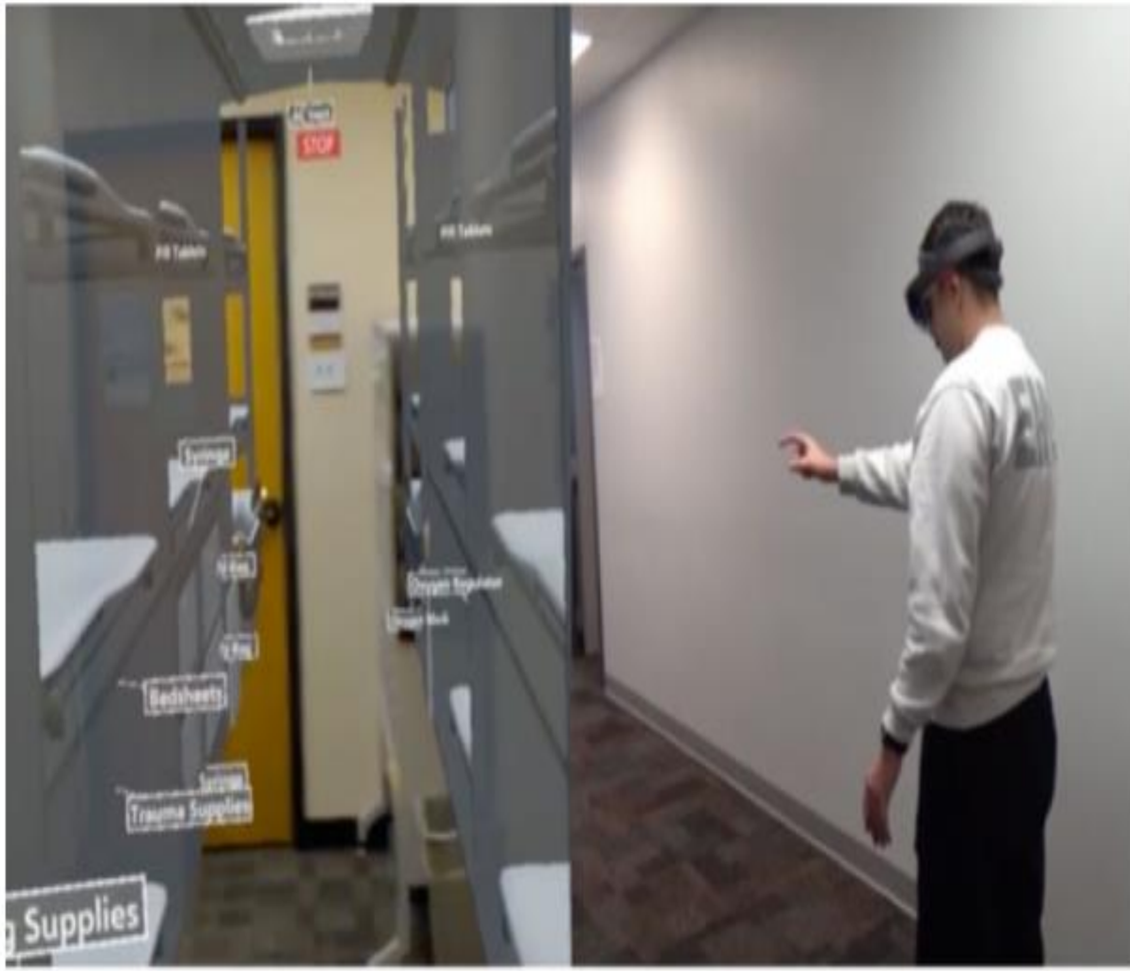
https://www.ems1.com/ems-trend-report/the-ems-workforce-is-sounding-the-alarm?utm
https://www.naemt.org/WhatsNewALLNEWS/2023/02/07/states-strive-to-reverse-shortage-of-paramedics-emts?utm

Related Work

XR in disaster training: Prior research shows AR/VR/MR can improve disaster preparedness, hazard visualization, and simulation-based training *(Khanal et al., 2022; Zhu and Li, 2021).*

First responder training: Earlier studies support immersive systems for training effectiveness and situational awareness, but most do not focus on **flood-specific MR in real space** *(Koutitas et al., 2021; Azpiroz et al., 2024; Oregui et al., 2024).*

This thesis: Extends prior work through a **mixed reality flood scenario** using **passthrough, depth-aware occlusion, shader-based water, and comparative evaluation** of Normal AR vs. Flooded AR.



Research Aim, Objectives, and Guiding Questions

Research aim:

To **design, implement, and evaluate** a mixed reality hurricane-flood training platform that integrates flood visualization, environmental controls, and measurable assessment.

Objectives

- Build a flooded MR environment with water, debris, dimming, and audio.
- Compare Normal AR and Flooded AR conditions using workload and task measures
- Integrate passthrough, depth, and occlusion for realistic hazard presentation
- Capture perceived realism, usefulness, and design feedback for future improvement.

Guiding questions

- Does the flooded MR condition increase perceived workload?
- Does it affect accuracy and response time?
- Do users perceive the environment as realistic and training-relevant?

Research Hypotheses

Hypothesis 1 — Perceived Workload

Null hypothesis

H_0: No significant difference in NASA-TLX workload between Normal AR and Flooded AR.

Alternative hypothesis

H_1: Flooded AR will produce significantly higher perceived workload than Normal AR.

Hypothesis 2 — Task Performance

Null hypothesis

H_0: No significant difference in task accuracy or response time between Normal AR and Flooded AR.

Alternative hypothesis

H_1: Flooded AR will reduce task accuracy and increase response time relative to Normal AR.

Hypothesis 3 — Realism and Training Value

Null hypothesis

H_0: Participants will not perceive the MR flood environment as realistic or training-relevant.

Alternative hypothesis

H_1: Participants will rate the MR flood environment as realistic and valuable for first responder training.

Methodology

Three-phase development and calibration workflow

Design	Implementation	Validation
• Rising water	• Shader Graph water surface	• Rendering stability
• Floating debris	• Passthrough + depth-aware occlusion	• Controller interaction check
• Reduced visibility	• Meta XR SDK integration	• Occlusion consistency
• Rain, wind, and water audio	• Researcher control menu	• Pre-study calibration

Why mixed reality instead of only AR or VR

AR

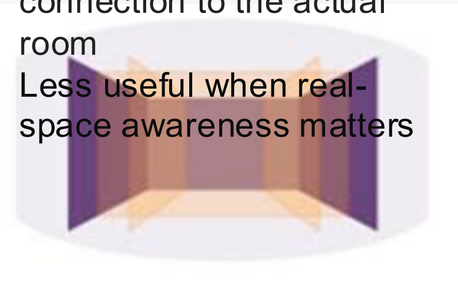
Adds overlays to the real world
Good for labels and guidance
Limited environmental integration

MR

Blends virtual hazards into the real room
Supports passthrough, depth, and occlusion
Best match for floodwater inside a physical space

VR

Fully virtual environment
High immersion but weaker connection to the actual room



Less useful when real-space awareness matters

Purpose of Mixed Reality:

- The participant remains in the real room while hazards are introduced into that same space
- Floodwater must look spatially grounded rather than like a flat overlay
- Depth-aware occlusion helps furniture and surfaces interact visually with the virtual water
- This supports realism, hazard interpretation, and representativeness

Platform Used

TECHNICAL STACK

This study was deployed on Meta Quest 3s. For future broader deployment, the same MR workflow is relevant to the Quest 3 family, including lower-cost devices in the same ecosystem.

Hardware Features

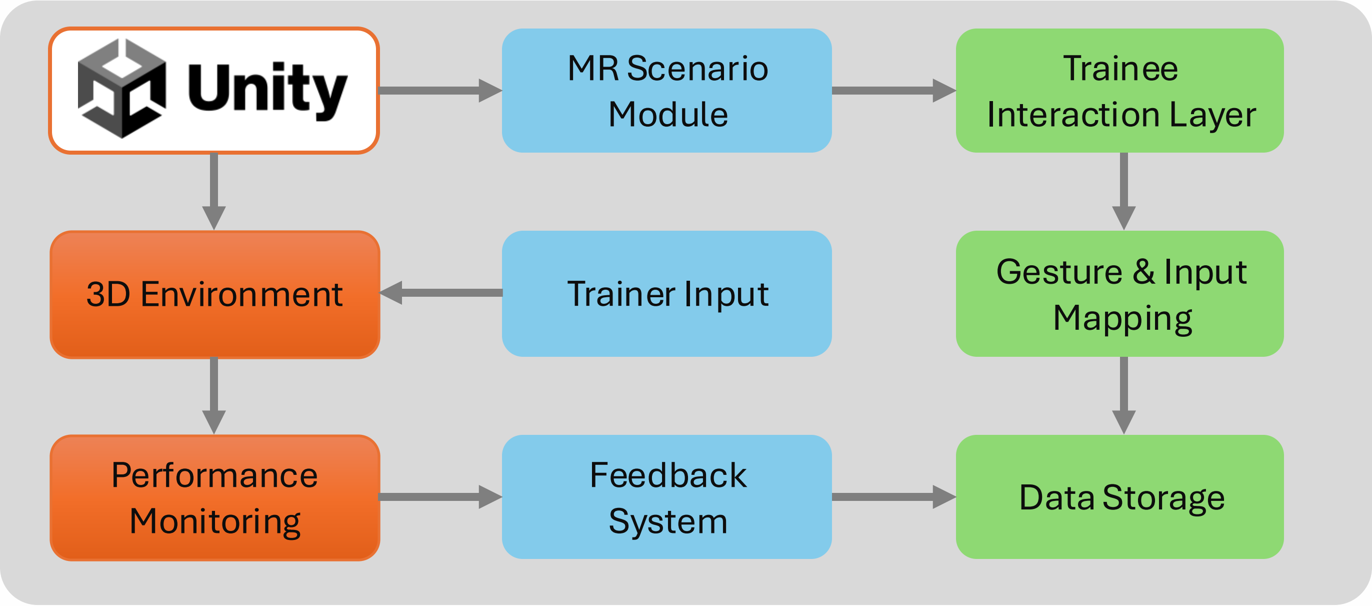
- Passthrough MR keeps users visually connected to the real room.
- Controller interaction supports reliable in-headset task flow.
- Environment depth supports occlusion of virtual floodwater by real objects.
- Meta Quest 3S supports both hand gestures and controller-based interaction, enabling intuitive user input while maintaining reliable task execution within the mixed reality environment.

Platform used

Software stack

Engine	Unity
Rendering	Universal Render Pipeline (URP)
MR framework	Meta XR SDK with passthrough
Depth feature	Environment depth / occlusion
Visual water	Shader Graph based material
Code	C#

System Design: MR Training Platform



Key Features

- Scenario Library: Modular design for multiple emergency situations
- User Interaction: Hand gestures, gaze tracking, and contextual feedback
- Training Flow:Tutorial → Simulation → Evaluation
- Data Capture: Completion time, accuracy, critical errors (for research analytics)

Passthrough, depth API, and occlusion

Real room → Passthrough view/Quest Camera → Environment depth → Occlusion logic → Floodwater rendered inside the room

Passthrough keeps the participant visually connected to the real environment

Depth API estimates the geometry of nearby real objects and surfaces

Occlusion uses that depth information so virtual water is hidden where real objects should be in front

This reduces the “overlay” look and makes water appear physically grounded

Occlusion improves realism and representativeness.

Water Shader

Base geometry

A floor-aligned water body was placed in the rescue space and treated as the visual flood layer.

Visual motion

Noise / wave-like movement and visual variation

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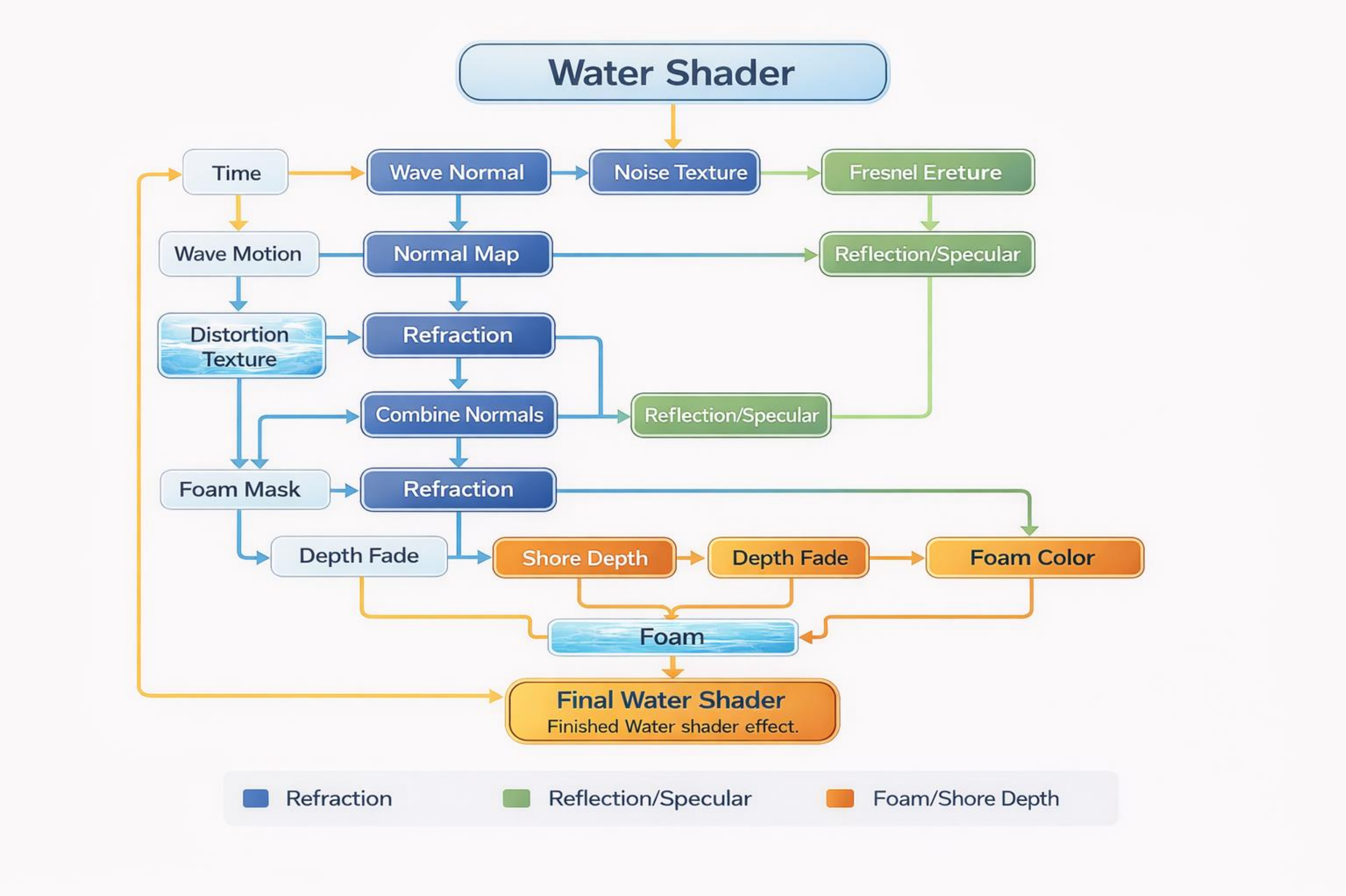


Parameter control

Water level was exposed through the researcher menu to vary perceived severity and support calibration.

Depth-aware alpha

Real-object depth reduces water visibility where occlusion should occur

Proposed MR Training Environment

Floodwater
Shader-based water body with adjustable level and depth-aware occlusion.

Hazards
Debris and clutter cues to represent unstable indoor flood conditions.

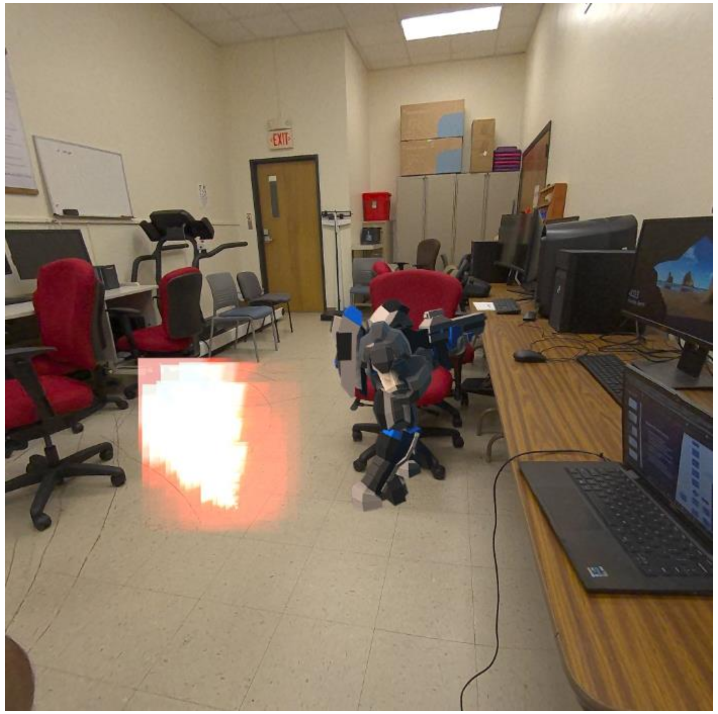
Atmosphere
Rain / wind / water audio and dimming to increase stress and realism.

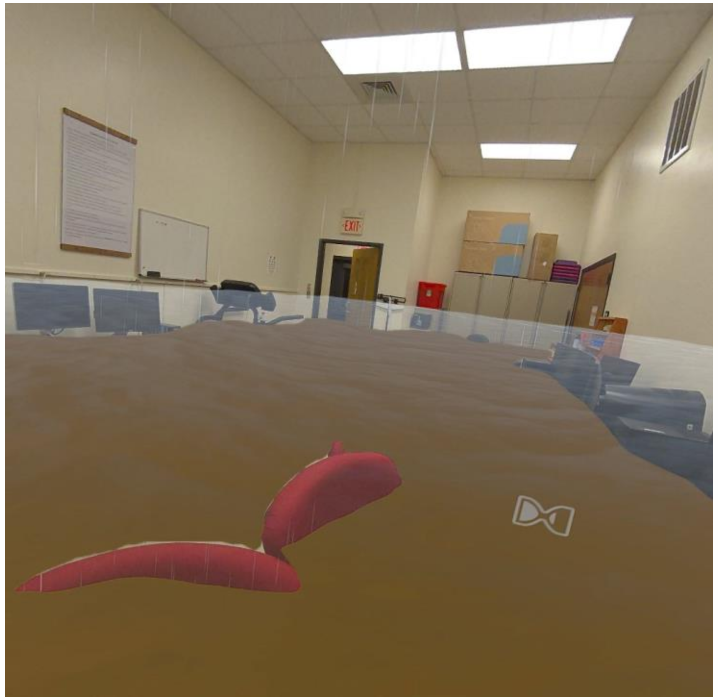
Control
In-headset menu for water, sound, and lighting calibration.

Normal AR
Baseline rescue environment without major flood hazards.

Flooded AR
Hazard-intensified state designed to alter environmental interpretation and operational pressure.

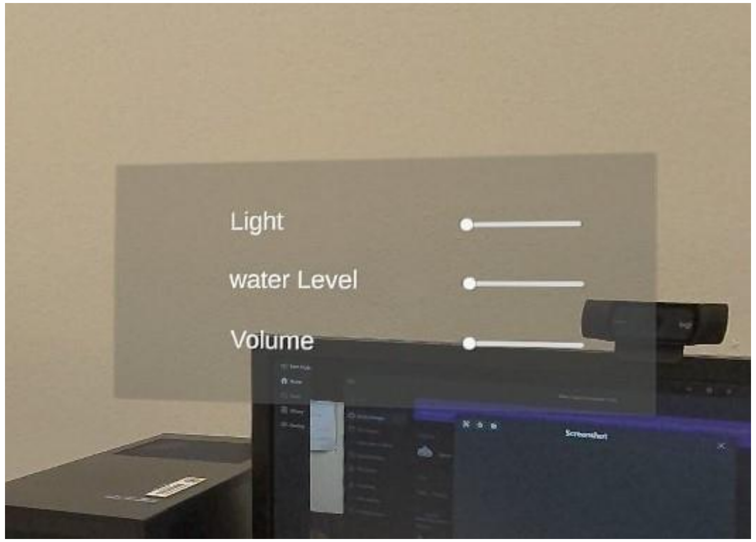
Demo



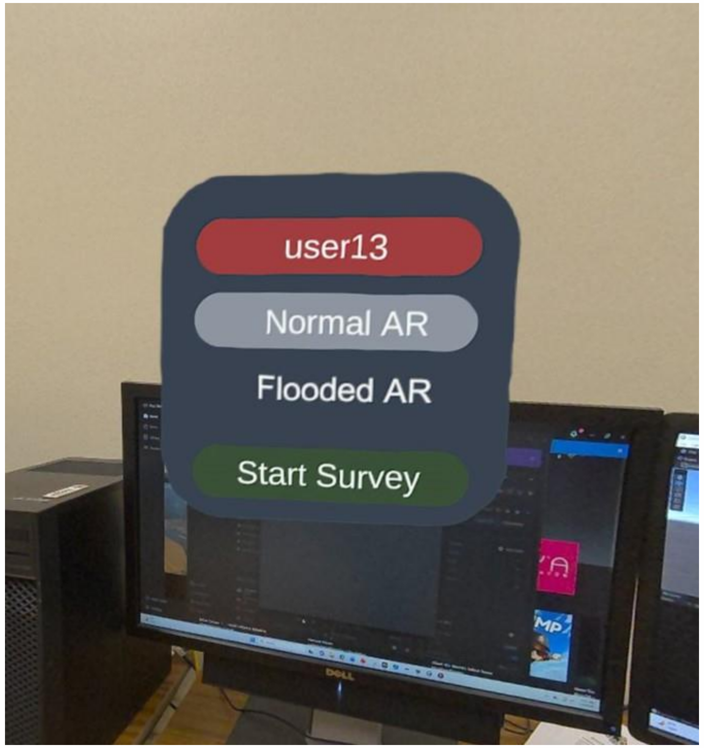


MR Environments with rising water level

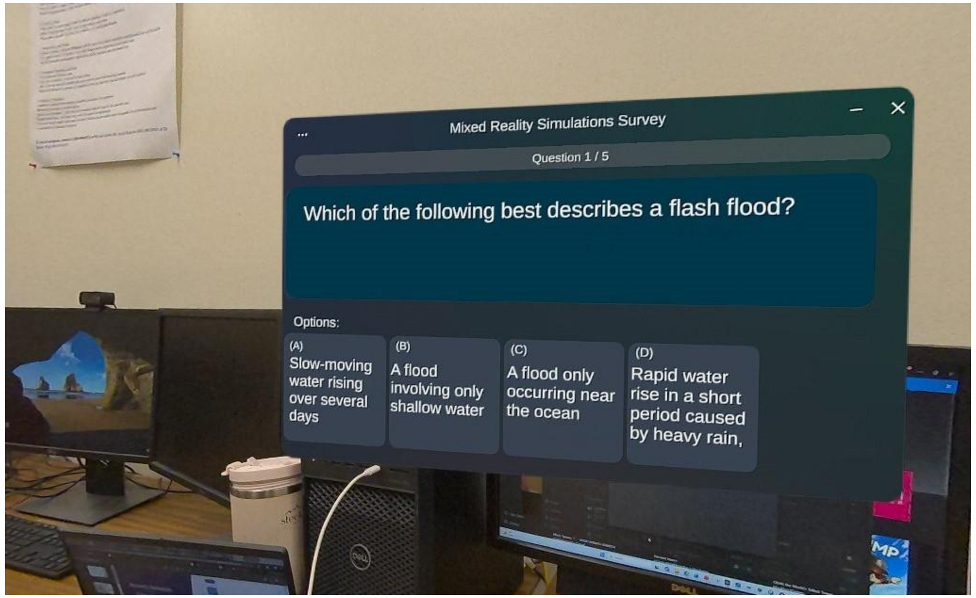
UI Design



Control Panel

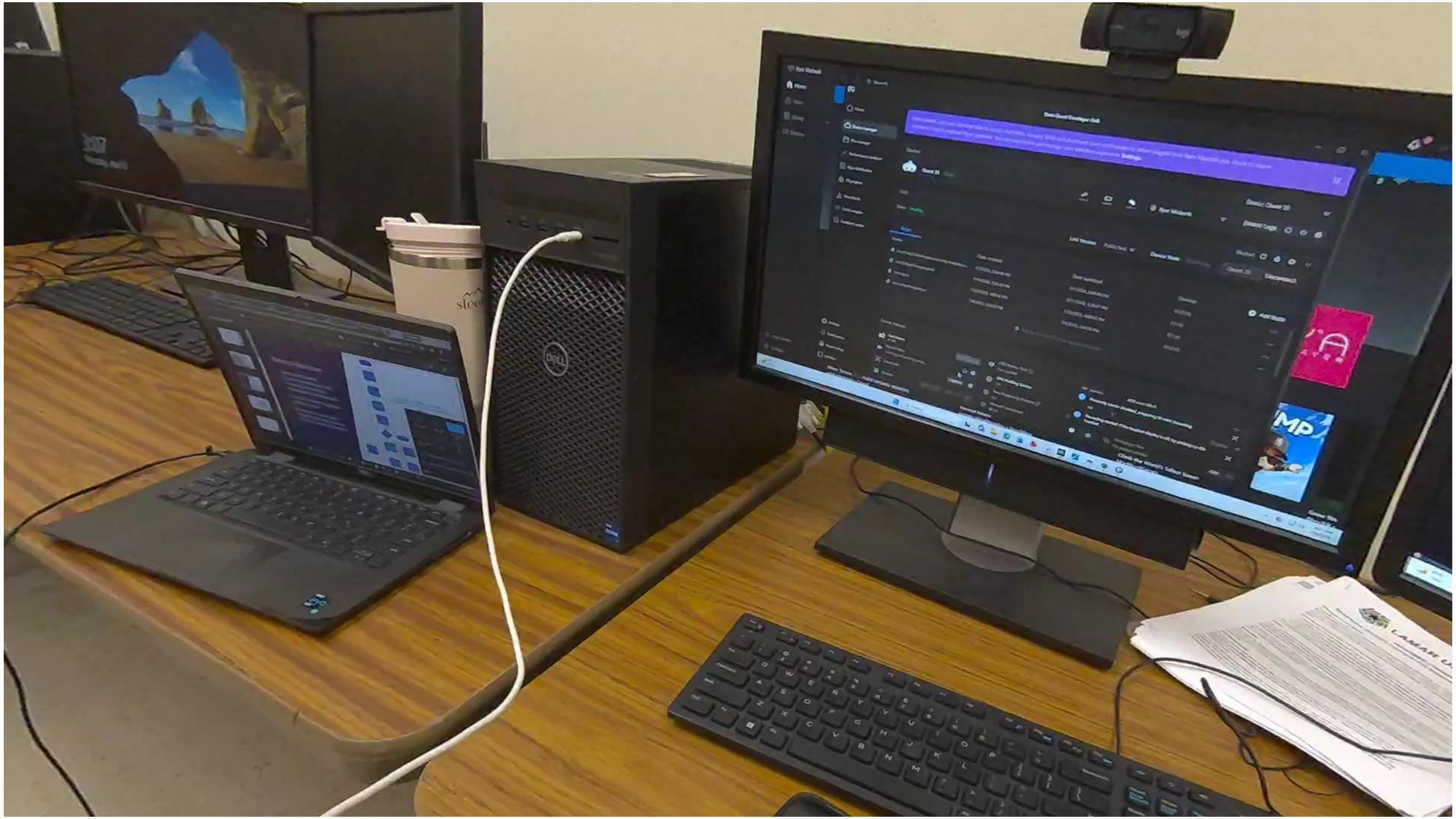


Survey panel



Question Panel

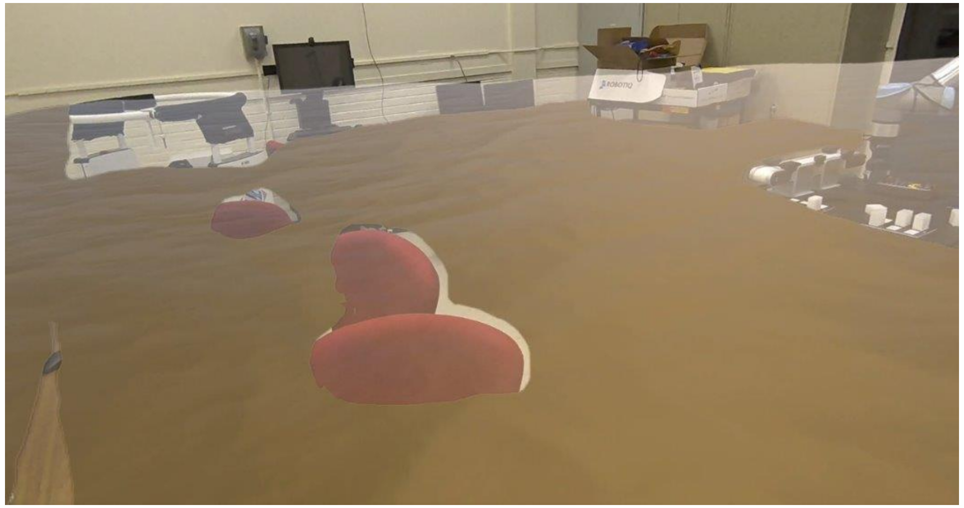
Demo



User Study Design

- A within-subjects counterbalanced crossover design was adopted, with two experimental conditions:

Condition A
Normal AR



Condition
Flooded MR

Experimental procedure

1. Participant ID and order selection
2. Condition 1 exposure in headset
3. External NASA-TLX for task 1
4. In-Quest question block for that condition
5. Condition 2 exposure in headset
6. External NASA-TLX for task 2
7. Remaining in-Quest questions
8. Final MR perception survey and interview

Assessment	Purpose	What it captured
In-Quest scenario questions	Objective task evaluation inside MR	Correctness, response time, and condition-based task performance
NASA-TLX after each condition	Subjective workload evaluation	Mental demand, physical demand, temporal demand, effort, frustration, perceived performance
Final MR perception survey	System-level user judgment	Realism, comfort, clarity, situational awareness, training value, and recommendations
Open-ended questions	Design improvement insight	What felt realistic, what failed, and what users want added next

Sample and analytical datasets

Participant structure

16 participants
8 completed A-B
8 completed B-A
5 questions per condition

Analytical datasets

Source	Rows	Key variables
NASA-TLX	32	Six subscales, Raw Score, Weighted Score
In-Quest responses	160 usable response records	Question ID, selected answer, correct answer, correctness, response time
Session summary	16	Sequence order, total correct, accuracy, average response time
Final MR survey	15 uploaded participant files	Closed-ended ratings and open-ended feedback

Statistical Approach

- **Descriptive statistics** were first computed for all major outcomes, including NASA-TLX scores, accuracy, response time, and final survey responses.

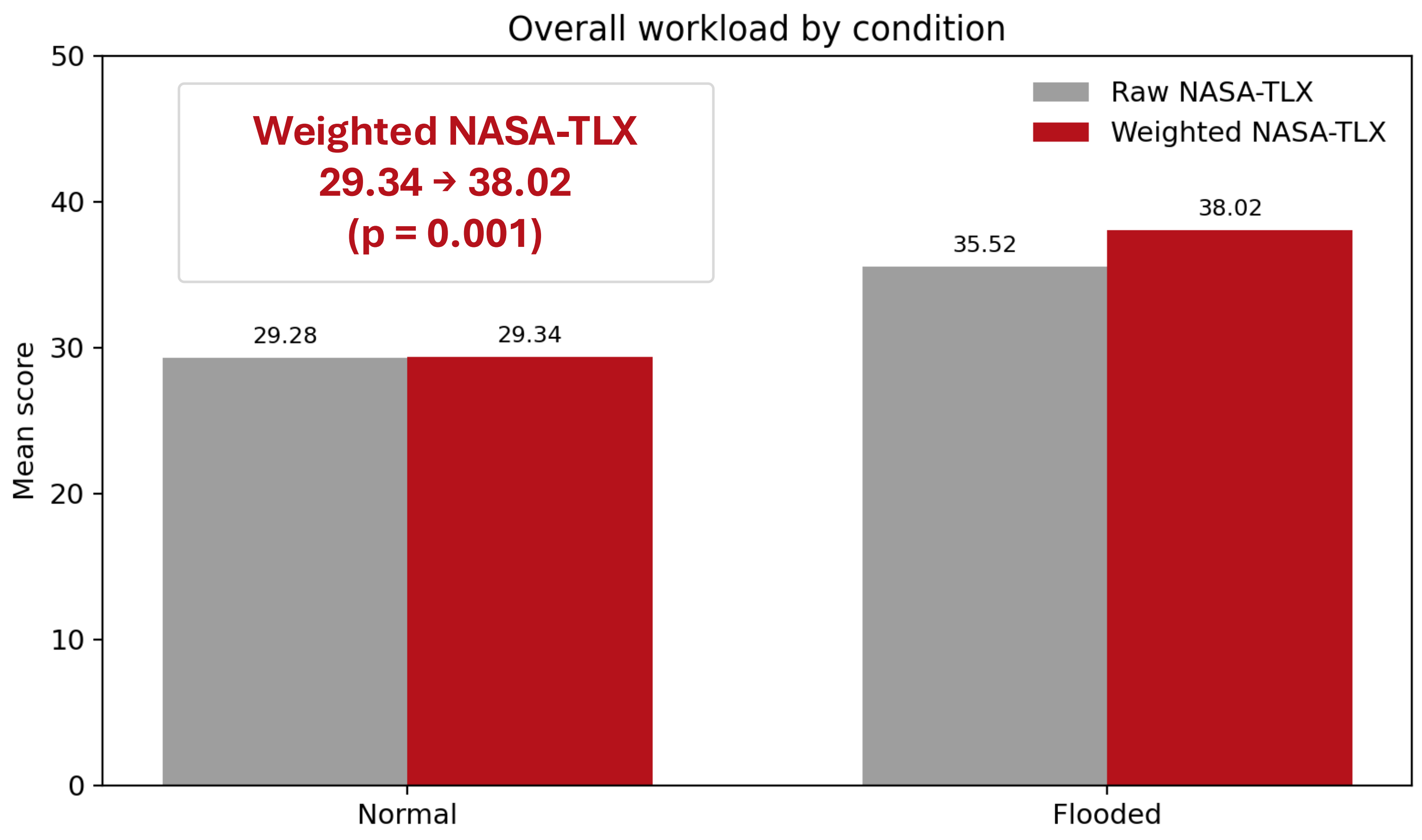
- **Paired condition comparisons** were then performed because each participant completed both the Normal AR and Flooded AR conditions, creating a within-subject dataset.

- **Normality of paired differences** was checked before inferential testing to determine whether a parametric or non-parametric test was more appropriate.

- **Non-parametric testing was used where assumptions were not satisfied**, making the analysis more suitable for the sample size and response distribution.

- **Sequence effects** were also examined by comparing patterns across the A–B and B–A groups.

Results: overall NASA-TLX workload

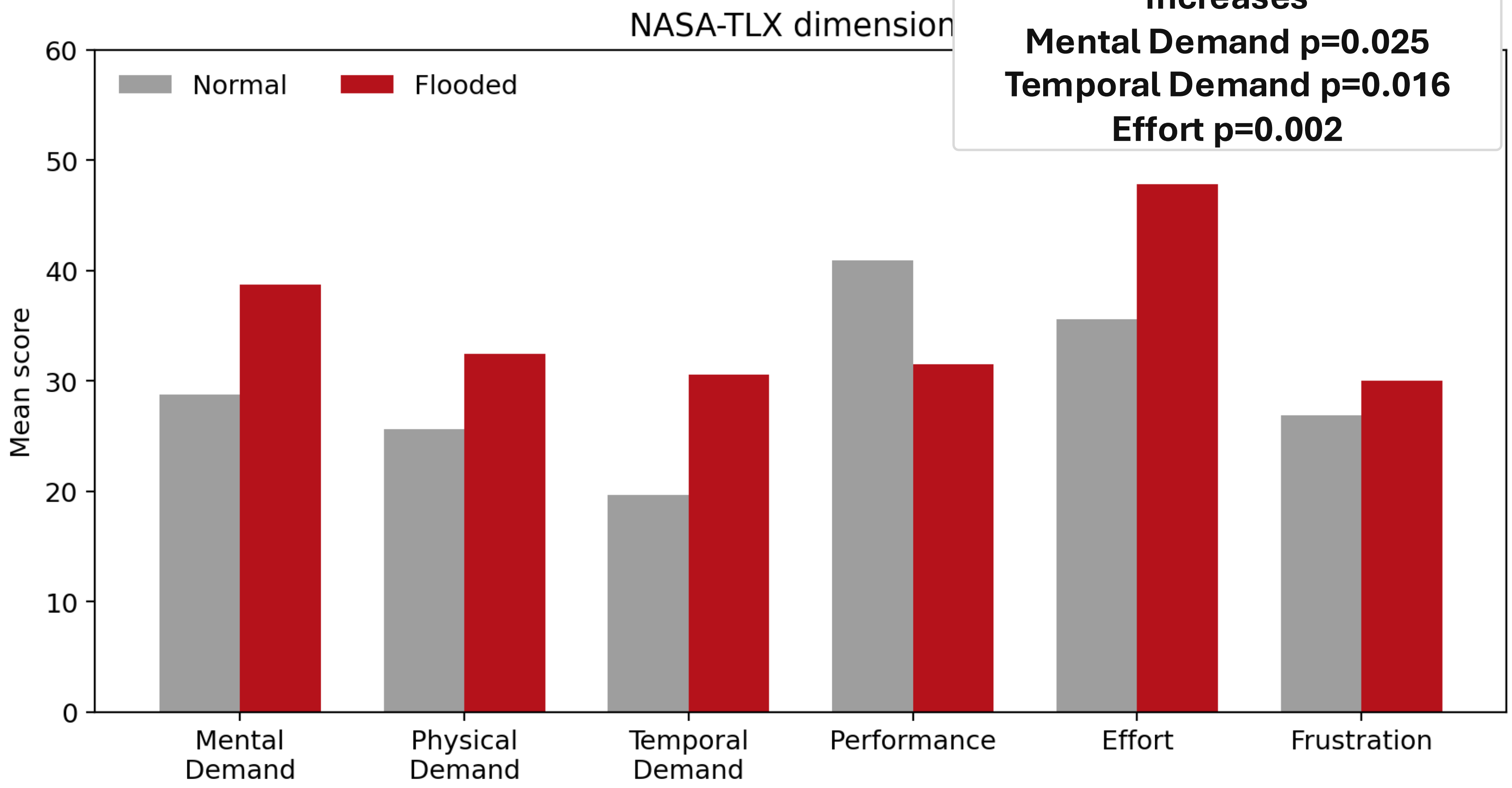


The weighted NASA-TLX score increased from 29.34 in the Normal condition to 38.02 in the Flooded condition, with a p-value of 0.001.

This indicates that the flooded condition significantly increased perceived workload relative to the baseline condition.

Flooded condition increased overall workload relative to Normal AR.

Results: NASA-TLX dimensions



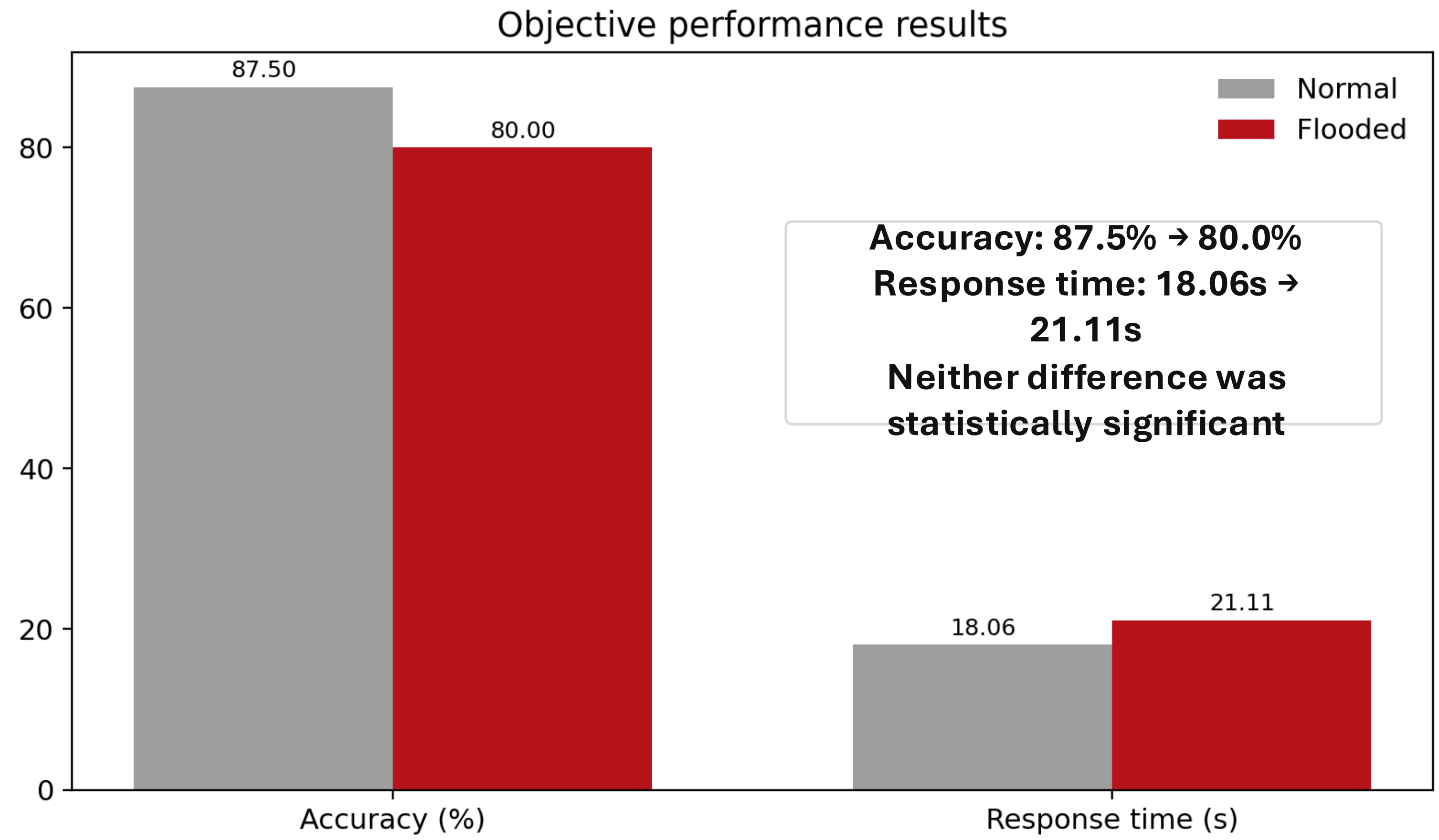
Significant overall increases
Mental Demand p=0.025
Temporal Demand p=0.016
Effort p=0.002

Largest increases were observed in mental demand, temporal demand, and effort.

Mental demand increased with a **p-value of 0.025**. Temporal demand increased with a **p-value of 0.016**. Effort increased with a **p-value of 0.002**.

These findings suggest that the flooded environment was experienced as more mentally demanding, more time-pressured, and more effortful than the normal condition."

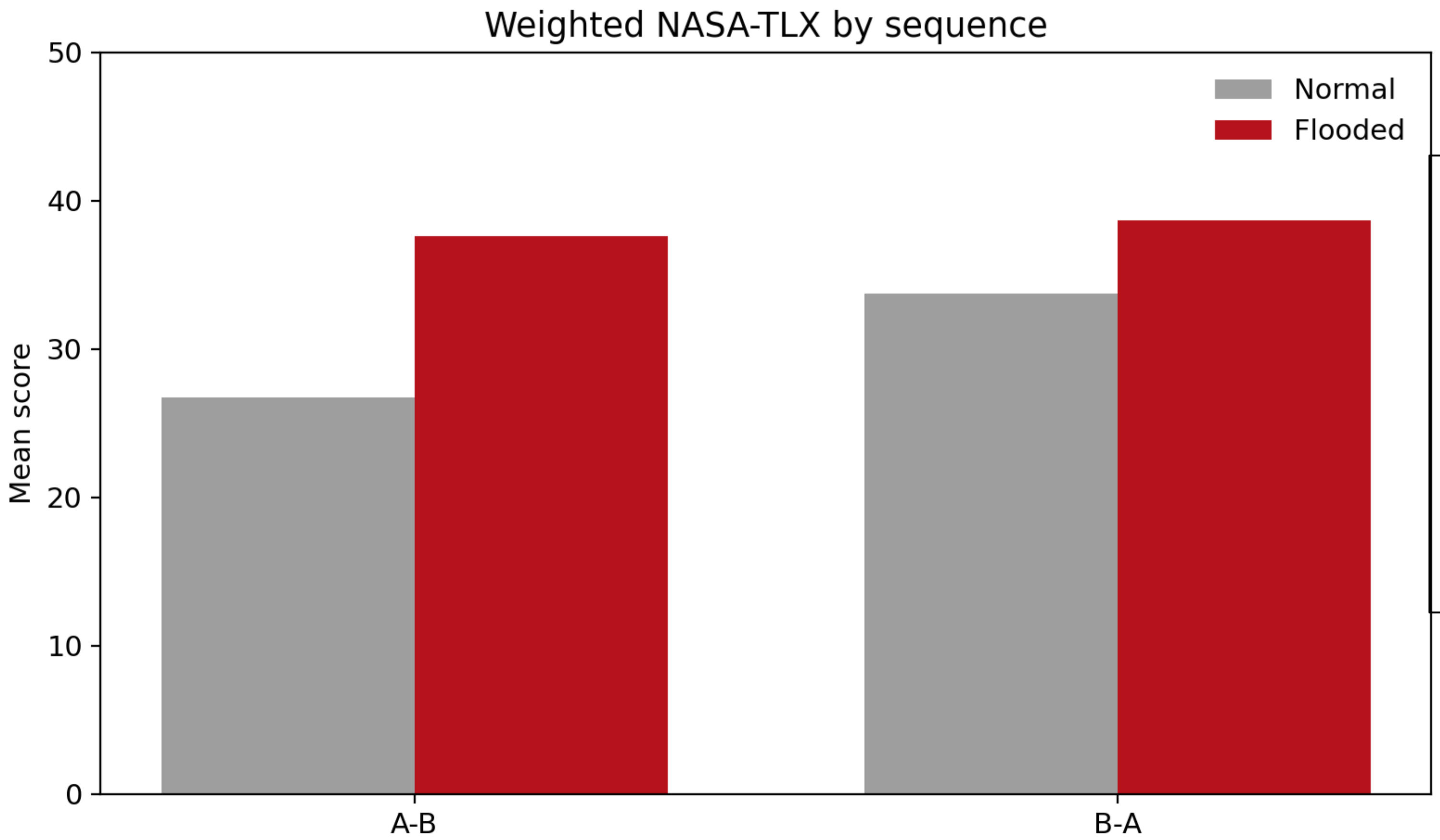
Results: objective performance



Objective performance shifted less than perceived workload.

The main impact of the flooded environment was more clearly seen in perceived workload than in raw task performance

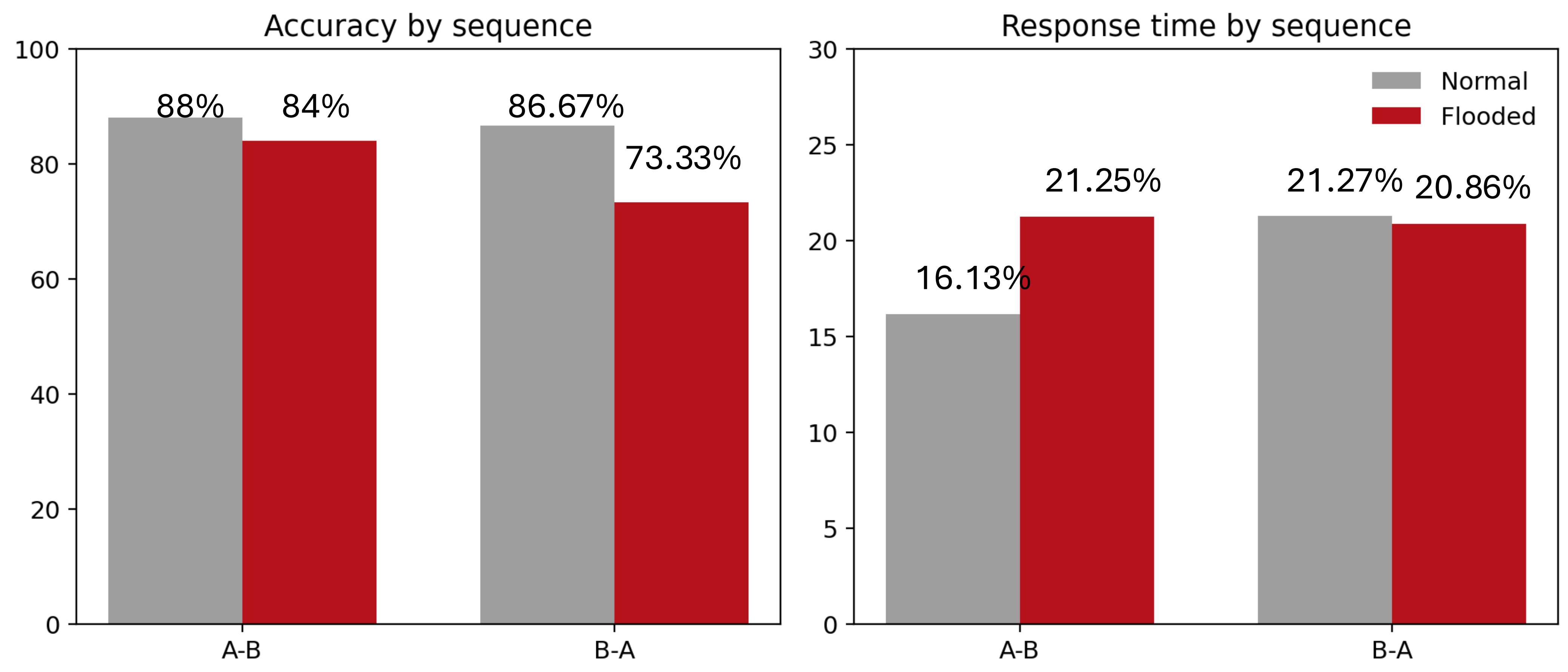
Results: sequence effects on workload



The workload increase was more pronounced when participants experienced the Normal condition first.

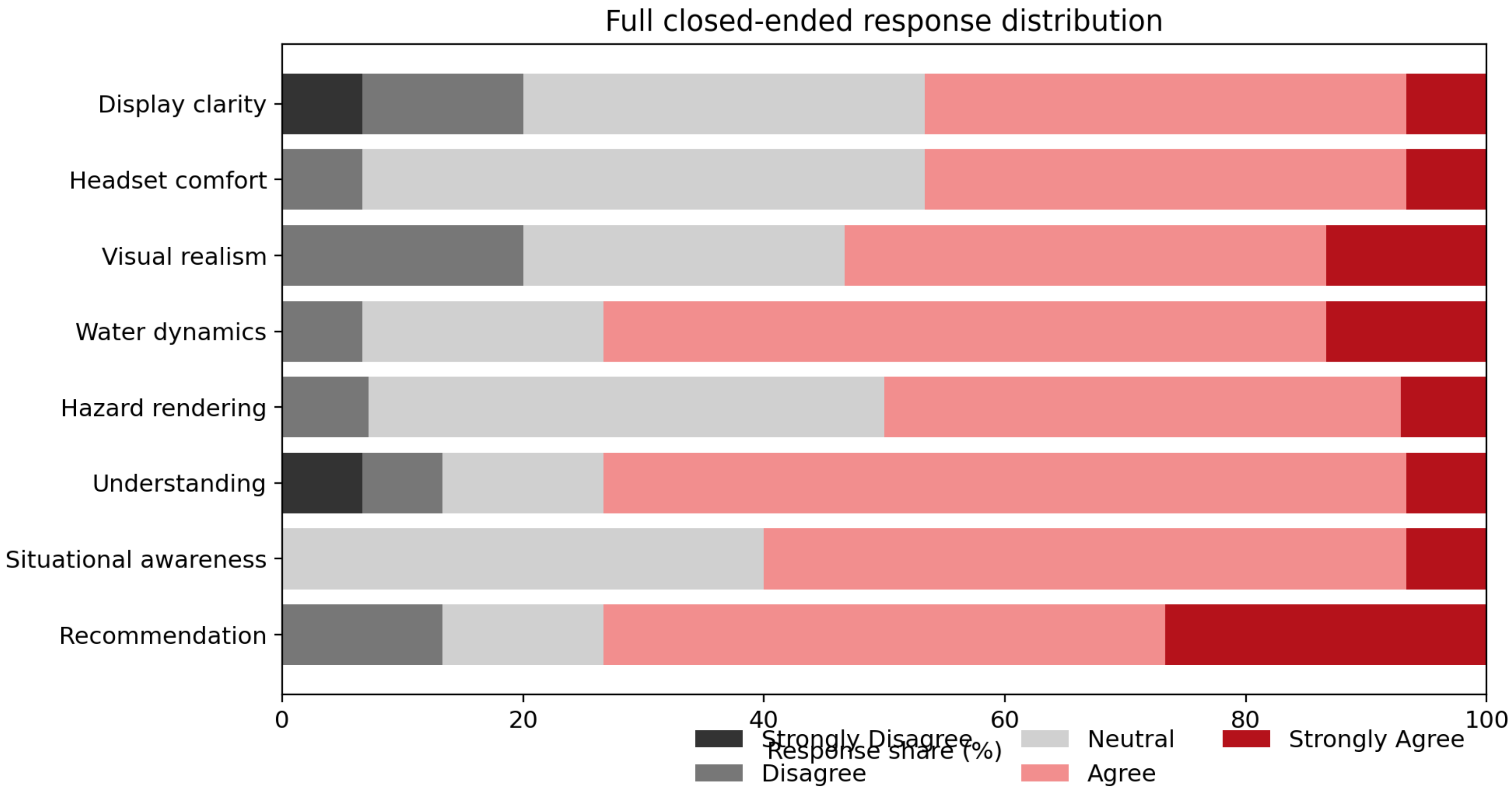
The increase in workload was more pronounced when participants experienced the Normal condition first and then the Flooded condition.

Results: sequence effects on objective performance



Order influenced the pattern of accuracy and response time, supporting the need for counterbalancing.

Final MR survey: full response distribution

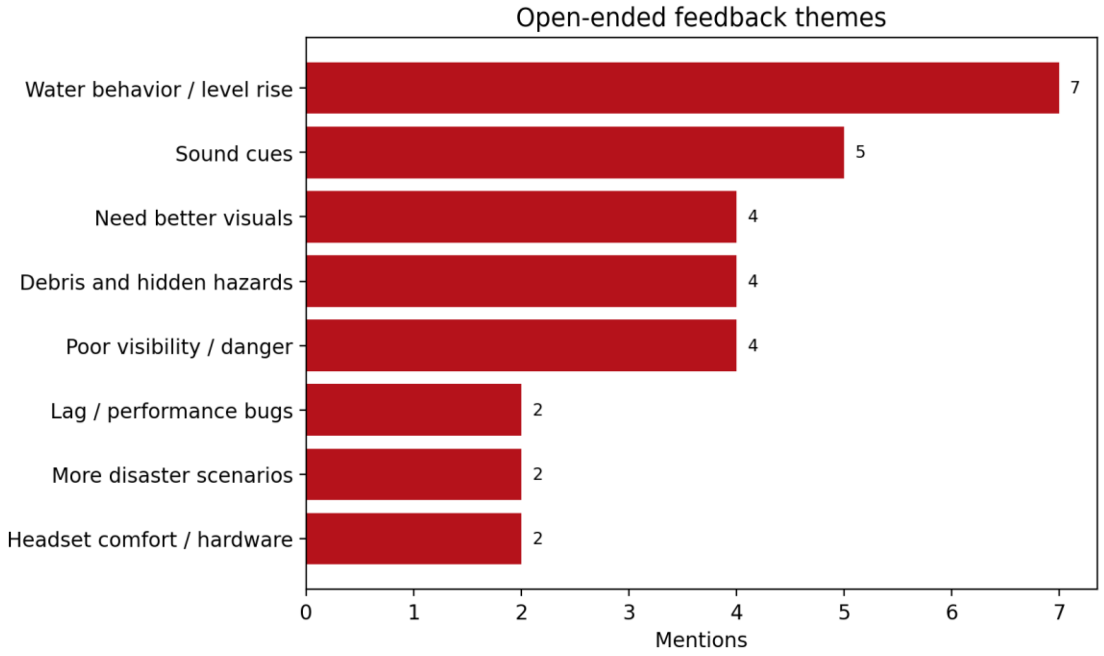


Responses were especially favorable for the believability of water behavior, understanding of flood conditions, and overall training relevance

At the same time, comfort and display clarity were more mixed

Participants were generally positive, but comfort and display clarity remained mixed.

User feedback and open-ended responses



Representative feedback

"The rising water level, loud sound of flowing water, and floating debris made the environment feel dangerous and real."

"The lag when it came across objects outside of the augmented reality made it seem less realistic."

"Including a transitional animation, like showing a source of the flood water, could improve immersion."

Themes coded from open-ended responses: water behavior, sound cues, debris/visibility, visual refinement, lag, and requests for more scenario types.

Interpretation of Findings

The flooded MR condition successfully increased perceived task demand, which means the manipulated environment felt more operationally challenging.

Objective performance changed only modestly, suggesting the main effect was not simply slowing users down but increasing cognitive burden.

Perception survey results show clear educational value: users believed the system improved understanding of water behavior and was worth recommending.

Open-ended feedback shows the strongest design wins were water behavior, sound, and danger cues; the biggest weaknesses were lag, comfort, and visual refinement.

Current Limitations

1. Modest sample size limits the strength of statistical inference.
2. Hardware comfort and occasional lag reduced realism for some users.
3. Objective measures were limited to question accuracy and response time.
4. The scenario focused on a specific indoor flood context rather than a full multi-hazard training curriculum.

Conclusion

A depth-aware mixed reality flood environment can serve as a meaningful supplemental training tool for first responders by increasing hazard realism, perceived workload, and user engagement without requiring live disaster exposure.

- Flooded MR successfully increased perceived task demand.
- Users responded positively to realism cues and training value.
- The system demonstrates promise as a scalable supplemental training tool.

Next step: Improve realism, stability, and breadth of scenario coverage.

Future Work

- Refine water rendering, transitions, debris behavior, and overall visual fidelity.
- Improve comfort, interaction reliability, and rendering performance for longer sessions.
- Expand beyond flood response into additional hazard scenarios such as storm surge, power loss, and structural damage.
- Evaluate richer outcomes such as hazard recognition, decision quality, and retention over time.
- Scale the study with a larger participant sample and more formal training comparisons.

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Thank you

Questions and discussion

Advanced Mixed Reality Training for First Responders in Hurricane Scenarios