CoMap: A Collaborative 3D Sketch Mapping Game to Engage Spatial Communication in Search and Rescue

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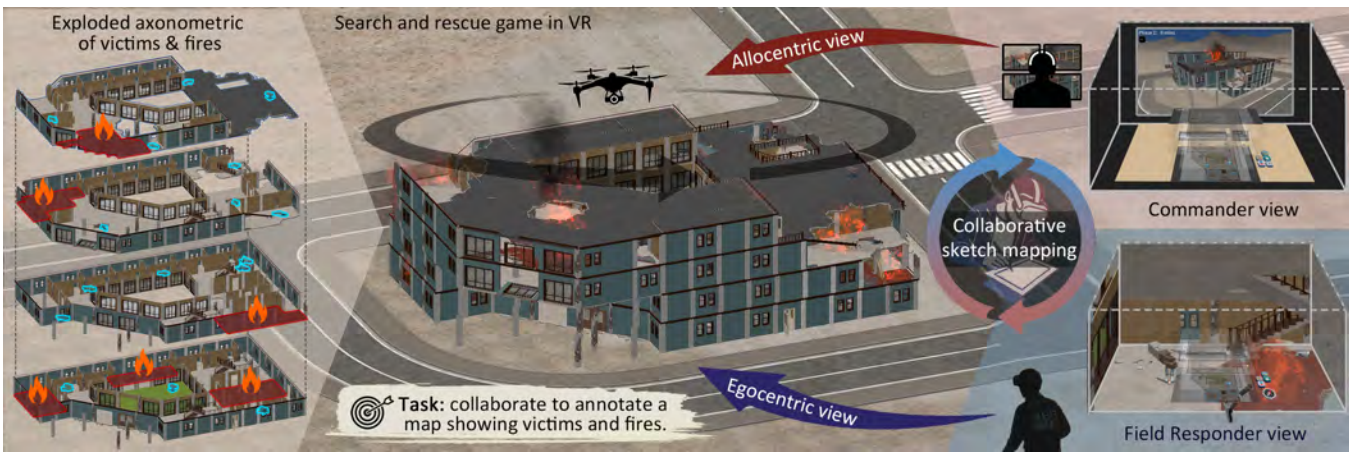

Figure 1: This paper presents a virtual reality search and rescue fire-based training game, involving a Commander with an *allocentric* view (via drone and base maps) and a Field Responder with an *egocentric* view, navigating the scene, verifying hazards, and reporting findings. To align asymmetric knowledge within heterogeneous teams, we introduce CoMap, a first-of-its-kind collaborative 3D sketch mapping interface that provides a shared workspace for distributed teams to co-maintain a map as a visual reference, supporting spatial communication and collective spatial cognition.

Abstract

Search and rescue (SAR) is a complex teamwork environment that requires efficient spatial communication between commanders and field teams with heterogeneous perspectives and asymmetric information. Maps are central artifacts in SAR, yet they are also a space of technological tension due to constantly changing situation at disaster sites. Sketch mapping is an effective method of externalizing and communicating spatial understanding, increasing situation awareness in spatial decision-making tasks including SAR. Current paper-based sketch mapping in SAR struggles to handle the three-dimensional nature of physical space and remote collaboration. We propose CoMap, a collaborative 3D sketch mapping system validated in a virtual reality fire-rescue game. In a within-subject study with 13 commander–field team pairs, CoMap enabled more accurate and efficient spatial communication than conventional 2D sketch mapping. Communication analysis further showed that CoMap fostered proactive descriptions. We distill three design implications for next-generation mapping tools to advance SAR training and real-world operations.

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CCS Concepts

• **Human-centered computing → HCI theory, concepts and models**; *Mixed / augmented reality*; User interface toolkits.

Keywords

Spatial communication, 3D sketch map, extended reality, search and rescue, collective spatial cognition

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Figure 2: Paper maps support (a) field responders' route planning and (b) commanders' tactical coordination. Photos from the 2023 Turkey earthquake, consented by a commander during expert interviews (Section 3).

1 Introduction

Search and rescue (SAR) is a time-critical disaster-response activity requiring careful spatial communication and collaboration between multiple responders [4, 33, 42, 77]. SAR field responders physically search technologically inhospitable environments whose geography may no longer match the data on hand (e.g., burned buildings, earthquake damage) [4, 47]. SAR teams are distributed, with field responders in the operational area (e.g., "hot zone") having a first-person *egocentric* perspective while command teams outside plan and offer support with an *allocentric* view that looks in [4, 42, 77] (see Figure 2). To save lives and property, SAR responders must use spatial communication to build a collective understanding of the environment, search it, make plans, and enact rescues [4].

This study explores the use of sketch maps, a long-standing practice in SAR [4, 32, 47, 77] that has received limited methodological attention in research on leveraging advanced technology for spatial communication. Conventional approaches center on verbal reporting or asynchronous two-dimensional (2D) mapping practice, yet incident sites are three-dimensional (3D) and subject to dynamic change. This restricts complex spatial communication [43] and makes shared awareness of the dynamic environment difficult [22]. We examine tool design in the context of asymmetric collaboration in SAR, which arises from the spatial and organizational separation of personnel operating in distinct environments [4, 10].

Guided by a formative study with literature review, iterative critique from a coauthor, and expert interviews, we developed *CoMap*, a collaborative 3D sketch mapping training system in virtual reality (VR) that:

(1) incorporates multimodal externalization tools for efficient map annotation and spatial communication;
(2) supports map synchronization in a shared visual workspace for collective sensemaking;
(3) supports specific interfaces tailored to distinct roles and activities of SAR; and
(4) supports incident management by data logging, sharing, and reconstruction.

While present technology is insufficiently robust to be used in the field, we envision the importance of information and immersive technology in future disaster response (e.g., as in [5, 50]). To evaluate its impact, we conducted a user study with 26 participants (13 dyads) in a representative SAR scenario in which rescuers are working in a recently collapsed building that is on fire in several places. We also conducted expert interviews with nine SAR experts to evaluate CoMap from a professional perspective. We address the following research questions:

RQ1. Does collaborative 3D sketch mapping enhance efficiency and accuracy, as well as user experience, while reducing task load in SAR compared to conventional 2D sketch mapping?
RQ2. How does users' communication behavior differ between collaborative 3D sketch mapping and conventional 2D sketch mapping?
RQ3. How does users' communication behavior using collaborative 3D sketch mapping inform the design of future sketch mapping tools for SAR training?

This study is a first-of-its-kind step to inform future larger-scale investigations on the potential of introducing asymmetric collaborative 3D sketch mapping in SAR missions and training for wider types of landscapes, such as in the urban, wilderness, and maritime environments [66]. We contribute:

(1) Design, implementation, and evaluation of CoMap: A VR/AR tool for collaborative 3D map annotation by heterogeneous SAR teams in multi-story buildings.
(2) A set of design objectives for future VR/AR-based SAR training systems, derived from a formative study with nine SAR experts.
(3) Empirical insights and design implications from a user study (n = 26, 13 dyads) and expert interviews (n = 9).

2 Related Work

We provide insights into the nature of disaster response – practice, cognition, and the role of maps. We conclude the section by looking at prior HCI research in this space.

2.1 Disaster Response Practice

Disaster response collectively refers to a range of activities that aim to protect life or property during an incident [4, 5]; *incidents* are events that endanger human lives and property and may be natural or human-made. Practitioners may use more specific terms, but, in general, we conceptualize urban search and rescue (USAR) and wilderness search and rescue (WSAR). USAR is carried out in heavily damaged or destroyed populated, built environments, while WSAR usually involves locating and saving missing subjects or objects outside of civilization [31, 66]. Disaster response practice varies country-to-country, with a range of support available (e.g., local, volunteer responders versus federally funded, well-equipped professional teams) [33–35, 37, 47]. The present research is informed by practice in a central European country and a North American country, of which the research team has knowledge.

Disaster response varies depending on the severity of an incident. For small incidents (e.g., single house fire), there may be a single incident commander in charge of one or two teams [79, 80]. Larger incidents scale up in terms of human power and organizational complexity; earthquakes and hurricanes often call for multiple large, federated teams that are overseen by a group of people in unified command, possibly involving heads of state [4].

2.2 Cognitive Foundations of Coordination in SAR

A foundational concept in spatial cognition is Tolman's notion of the "cognitive map" [76], the mental representation of spatial environments that can be organized in self-centered (*egocentric*) or environment-centered (*allocentric*) frames of reference [28]. In SAR, command teams predominantly rely on allocentric knowledge to judge the positions of landmarks (e.g., fire, victims, building structure) without reference to their own position, whereas field responders operate primarily from egocentric knowledge based on on-site observations and limited allocentric input via annotated maps and GPS information [4, 28]. Field responders risk becoming disoriented in environments lacking landmarks due to this imbalance.

To address such challenges, Montello's concept of *collective spatial cognition* –"a wide range of phenomena in which people solve spatial problems in human collectives" [22] – highlights SAR as a prime example of situations where spatial problems must be solved collectively. Effective collective spatial cognition enables distributed teams to integrate heterogeneous perspectives to carry out interdependent tasks, such as suppressing spreading fires while locating and rescuing victims in parallel. This capacity is closely tied to two interrelated processes: *sensemaking* – the collection and integration of data for decision-making [2, 86], and situation awareness – the ability to understand the current environment and anticipate its evolution [29]. Maintaining sensemaking and situation awareness in SAR is particularly challenging under time pressure, rapidly changing conditions, technological limitations, and variable team structures. Professional units, such as Swiss Air-Rescue and US state task forces, benefit from stable personnel, clear roles, and routine joint training, whereas volunteer-based organizations often face high turnover, heterogeneous expertise, and weaker shared mental models, making this process difficult [33–35, 37, 47, 51, 68, 77].

Cartographic interaction with paper and digital maps is central to these processes, serving as a shared external representation that supports collective spatial cognition, facilitates sensemaking, and sustains situation awareness during SAR operations [4]. We build on this foundation to examine how collaborative 3D sketch mapping can enhance spatial knowledge exchange across heterogeneous perspectives. Understanding practical map use in SAR, from traditional paper to emerging digital solutions, is therefore essential and is introduced in the next section.

2.3 Maps in SAR

Reading and annotating maps is a core component of SAR training and missions. Common artifacts include baseline pre-disaster maps, GNSS[1]-enabled digital maps, and sketch maps used for logging, communication, planning, and decision making [4, 32, 77]. Commanders use large paper maps to overview search areas and guide discussions [69], while field responders rely on waterproof maps for durability in extreme conditions and coordination with commanders [69]. Sketching on acetate overlays effectively tracks progress and plans next actions [11, 69], and SAR trainees must learn to read and create such sketches [4]. Digital mapping technologies range from web maps, mobile maps, desktop interactive maps, GNSS, and geographic information systems (GIS), supporting real-time tracking and coordination. For example, Norwegian volunteers use trackers to monitor field responders [37], while interactive desktop systems enable collaborative annotation, visualization, and planning [32, 49, 65].

Each method has its affordances and constraints. Digital maps offer visualization, spatial analysis, and data management capabilities but face barriers to adoption, such as funding, training, portability, and compatibility. Navigation and GIS-based mapping systems rarely enable both individual and collective activities [4]. Data from field responders is often poorly archived [26], and collaborative desktop systems require bulky hardware. Paper maps, by contrast, remain highly flexible in early search stages, supporting intuitive sketching and annotation when digital maps are unavailable [69, 75]. However, they suffer from static representations, inefficient synchronization, limited remote collaboration, difficulty in managing large volumes of data [69], and challenges in depicting complex 3D structures [46, 88]. Digitization and scanning of sketch maps also carry the risk of transcription errors [57] and delays, and make spatial analysis of map elements difficult.

Advances in AR and VR head-mounted displays (HMDs) enable combining the strengths of digital and sketch maps while mitigating their limitations. Future SAR systems should connect physical and digital data [4]. Mid-air sketching tools like Gravity Sketch [74] support direct 3D input, inspiring 3D sketch mapping approaches such as Kim et al. [46]'s concept and Xiao et al. [88]'s layered implementation, analogous to acetate sheets for multi-layer buildings. Recent work extends this direction with AI-driven sketch-to-terrain interfaces in AR [87] and 3D sketch mapping for collective navigation in WSAR [89]. Motivated by these constraints and innovations, we developed an AR/VR collaborative 3D sketch mapping tool that embeds teamwork as a central element in SAR and enables newcomers to intuitively represent complex 3D spatial information on a map. We

[1]"Global navigation satellite system". Note that the USA's Global Positioning System (GPS) is the most famous GNSS, but not the only one [83].

demonstrate the concept through a common SAR scenario: locating victims in a multi-layer building.

2.4 SAR in HCI

Research on SAR within HCI has been grounded in ethnographic studies of responders' practice and the creation of artifacts in response to needs in disasters. It is worth noting that few technologies are yet sufficiently robust to survive and support actual disaster response operations [51]. Generally, research is done on prototypes that are aimed at providing the right interface in the future, which is how the present research should be viewed.

Extensive fieldwork has established insight into the reality of SAR, firefighting, and other disaster response practices, with an emphasis on information sharing and communication [4, 23, 41, 52, 78, 81]. In particular, the work on USAR and WSAR highlights the way information is moving around in real time and the centrality of the need to augment maps [3, 4, 32, 43, 51]. Fischer et al. [32] use their insights to build a tabletop Augmented Bird Table digital map interface to support planning. These projects reveal key challenges in mapping methods, real-time information sharing, and field responder activity tracking. Among these observations, collective spatial cognition and collaborative decision-making emerge as critical assets across diverse SAR workflows.

Drone support and remote sensing to build egocentric and allocentric views is also a prior theme. LaLone et al. [50] envision a near-future where drones enable field responders to "mark up" a map for search. Jones et al. [43] introduced RescueCASTR, which enables photo and live streaming between command and field search teams to support contextual awareness. Sabet et al. [71] developed Squadrone, a drone-based telepresence system to support situation awareness and remote collaboration during SAR and broader aerial search applications. These prior works offered design implications on how modern SAR technologies could improve team cognition and collective spatial cognition [22, 51, 81].

In HCI, the research on distributed multiplayer games shows that annotations (i.e., freely drawn lines and shapes) result in quicker goal completion times than without using it [6]. Map-based hazard labeling is still generally icon-based, despite the value of more freehand approaches. Inspired by the impact of annotation in distributed multiplayer games [6, 77] and Augmented Bird Table [32], our work facilitates 3D annotations on base maps and explores how it could influence spatial-temporal interaction during simulated SAR missions.

3 Formative Study

To investigate how map technologies affect communication and coordination in SAR, we conducted a formative study to characterize practice, identify challenges, and derive design objectives. These design objectives were used to design and implement CoMap (Section 4). The study protocol was approved by the IRB board of the ETH Zürich.

3.1 Methods

The study had three components: (1) a review of SAR literature; (2) iterative critique from a coauthor with decades of SAR research experience (synthesizing prior interviews, questionnaires, and fieldwork); and (3) semi-structured interviews with nine SAR professionals. We conducted the first two components to design an initial prototype of CoMap, sufficient to have conversations with experts about it in the third component for improvement.

The experts (E1–E9) of the semi-structured interviews were recruited through professional and social networks and selected with a short survey (Appendix A.1). They reported 2 to 15 years of SAR experience ($M = 6.0$, $SD = 3.9$). Roles included six field responders and three participants with both command/field experience (E2, E5, E7). More demographic details appear in Table 1. All participants were compensated at local wage rates.

The interview protocol had two parts. The first covered mapping practices: training; use of paper, GNSS, GIS, and web/mobile maps; critical and missing geodata; and tool limitations with desired improvements. The second covered communication and collaboration: communication channels and limitations, and role-specific questions. The complete protocol is provided in the Appendix A.2.

The interview recordings were reviewed by the first author to collect insights. The work was exploratory and formative – descriptive coding was used to summarize our findings.

3.2 Challenges of Current Practices

We identify four recurring challenges in current SAR practices and summarize them below.

3.2.1 Outdated and Imprecise Map Data. In remote or mountainous areas, maps are often outdated or imprecise, making navigation harder, reducing efficiency, and increasing risk (Figure 3(a)). For instance, E4 recalled "*missing orientation and making great efforts to open up new roads*" due to imprecise map data. E2 noted that knowing local roads would allow teams to take shortcuts and operate more efficiently.

3.2.2 Lack of 3D Map Representations. Existing 2D and 2.5D maps (e.g., adding heights to 2D maps) do not clearly convey terrain elevation or building height due to visual obstruction and scale

Table 1: Characteristics of SAR experts involved in the semi-structured interviews.

ID	SAR Years	Role	Gender	Age
E1	7	Field Responder	Man	41
E2	3	Commander/Field Responder	Man	30
E3	4	Field Responder	Man	29
E4	4	Field Responder	Woman	36
E5	10	Commander/Field Responder	Man	50
E6	6	Field Responder (Logistics)	Woman	32
E7	15	Commander/Field Responder	Man	36
E8	2	Field Responder	Woman	32
E9	3	Field Responder (Firefighter)	Man	25

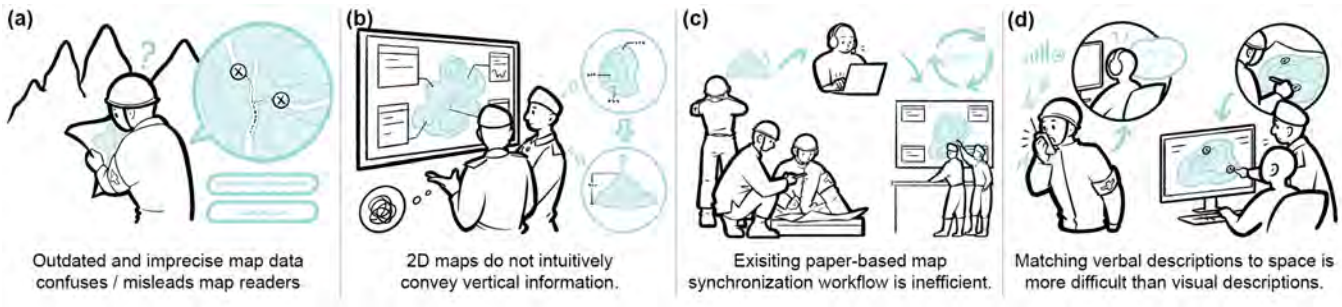

Figure 3: Challenges of current mapping and spatial communication practices. Illustration by an artist.

mismatch, leading to misunderstanding and cognitive overload (Figure 3(b)). E4 noted that "*too much layered data on a 2D map causes difficulty in reading and interpretation.*" E2 described 2D maps as a "*third-person bird's-eye view*" that requires mentally inferring vertical details, whereas "*3D maps let you see it directly, like a first-person view.*" E6 added that even with contour lines, key features can be missed: "*a cliff cannot be detected from the map if it is located between two contour lines.*" These limits can degrade decisions.

3.2.3 Poor Map Synchronization in Dynamic Environments. Operational maps are largely static and do not capture real-time changes at the front line. In dynamic incidents, especially fire scenarios, this reduces situation awareness and impairs decision-making. E7 described the current inefficient paper-based workflow: field responders annotate maps, photograph them, send the images to a liaison, and the liaison verifies, digitizes, and merges them into the command map, which needs to be updated every 10 minutes (Figure 3(c)).

3.2.4 Error-prone Voice Communication. Voice reports over radio are the primary means of communication in SAR, but they suffer from environmental factors such as delay, noise, signal loss, distance, or overlapping conversations, leading to misunderstandings [4, 51]. In contrast, map annotations provide persistent visual artifacts that are unaffected by such disruptions, can be revisited and clarified collaboratively, and offer unambiguous spatial context (Figure 3(d)). As E2 states, "*matching language descriptions to spatial contexts is not easy,*" highlighting the need to convey complex spatial information visually.

3.3 Elicited Design Objectives

To address these challenges and guided by the design implications of Alharthi et al. [4], we translated these research findings into three design objectives (DOs).

3.3.1 DO1 — Support collective sensemaking by shared visual workspace and map synchronization: Kraut et al. [48] found that a shared visual workspace improves communication efficiency and helps teams better understand the progress of tasks. Interactive shared maps allow teams to stay on top of each other's situations and activities, thus maintaining sensemaking [32, 49, 65]. Real-time data synchronization ensures consistent visualization and seamless map interaction within the shared workspace of all response teams to reduce the uncertainty of information [4].

3.3.2 DO2 — Support communication for complex, dynamic environments under time constraints by efficient externalization tools: Information in disaster environments is incomplete and dynamically changing [13], and there are strict time constraints on task completion times [63]. Such features make communication essential for team coordination and enhance search efficiency. Sketch mapping and verbal descriptions efficiently externalize cognitive maps and navigation experiences [9, 14, 24, 61]. Specifically, sketch maps are used to study route knowledge as well as wayfinding performance [70]. Verbal descriptions can create good visuospatial representations of cognitive maps [25] and are helpful in environments with limited visibility or restricted space.

3.3.3 DO3 — Support collective incident management by data logging, sharing, and reconstruction: Consolidating data from diverse sources, such as sketches and verbal reports, into a logging system provides permanent storage of information for efficient review and debriefing. Inspired by widely used distributed version control systems, which facilitate data management, collaboration, and version tracking, we acknowledge the decentralized and heterogeneous nature of communication and decision-making in SAR [3] and incorporate this principle into our system design.

4 CoMap Design & implementation

This section presents the concept of collaborative 3D sketch mapping and describes the architecture and core functions of CoMap.

4.1 Concept

This work is situated within the conceptual framework of *collaborative 3D sketch mapping* [89], a new sketch mapping paradigm that lays the groundwork for a future where geographically distributed users can interact, communicate, and share spatial information through intuitive sketching in VR/AR, coupled with other communication methods. This forward-looking concept combines the strengths of digital maps (i.e., editability, transferability, interoperability, archiving) with those of sketch maps (i.e., intuitive interaction, familiarity, ease of learning).

We envisioned that this concept would be particularly useful for users with heterogeneous perspectives to align their spatial awareness and understanding. Commanders synthesize information from various sources (e.g., national topographic maps,

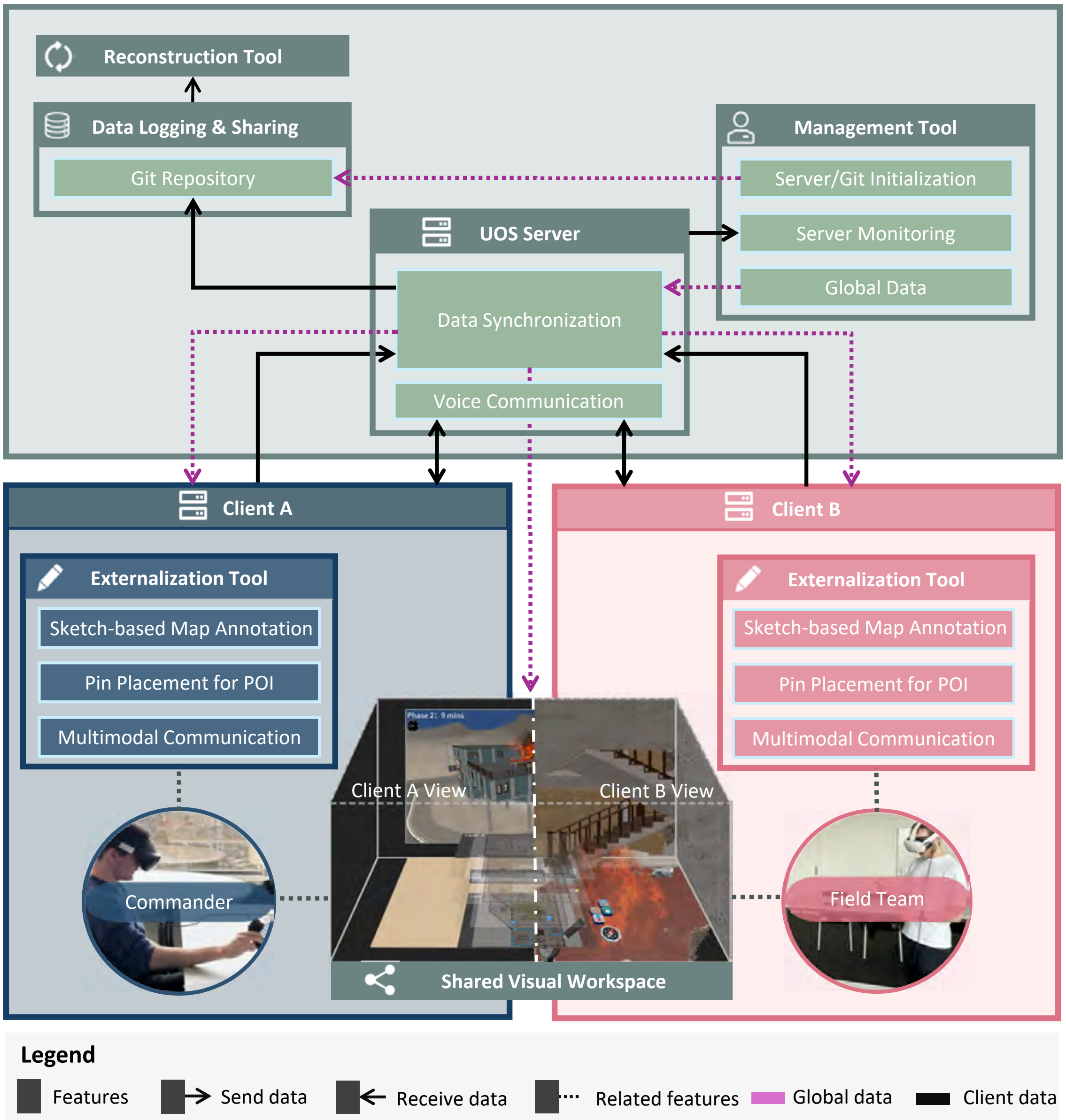

Figure 4: CoMap operates on a client-server architecture for data synchronization and voice communication. A management tool monitors the server and global data. Externalization tools include sketch mapping, pin placement, notes, photos, and videos. After each SAR mission, the externalization process is uploaded to a Git-based remote repository for data logging and reconstruction.

commercial maps, drones) [64], while field responders conduct on-site inspections, identifying traces or objects related to victims. Collaborative 3D sketch mapping integrates these perspectives into a shared map, facilitating situation awareness and enhancing task efficiency.

We implemented the concept in CoMap, a VR/AR tool for collaborative 3D annotation for the spatial information of multilayer buildings in SAR. It combines asymmetric information from geographically distributed users (e.g., commanders and field responders) into a single shared map. We hypothesize that CoMap improves map accuracy, measured by points of interest (POIs) localization and areas of interest (AOIs) delineation, while also reducing task load compared with traditional sketch mapping. The system configuration is shown in Figure 4. We acknowledge that long-term progressive development will be required for such a paradigm to be implemented in SAR practice. In Section 5, we present a simulated VR game study as a preliminary exploration to assess the feasibility and potential of our approach.

4.2 Data Synchronization and Management

4.2.1 Data Synchronization. Based on ***DO1***, CoMap operated on a client-server architecture and used *Sync Realtime* from Unity Online Services (UOS) [21] for real-time data synchronization. Figure 4 conceptually illustrates two clients (Commander and Field Responder), but additional clients can be added in practice.

To minimize coordination challenges within the time constraints of SAR missions, we define three types of operations for synchronization: (1) Add, creating new map elements (POIs and AOIs), (2) Edit, modifying existing map elements (e.g., repositioning a POI), and (3) Delete, removing existing map elements. Operations data is serialized into JSON format, then transmitted via the UOS server, and then forwarded to all clients. Upon receipt, clients deserialize JSON and process the data accordingly. For example, the client clones the Git repository after receiving the repository data. The client adds or edits map elements in a shared workspace (Section 4.3) when receiving AOI/POI data to ensure visualization consistency without complex negotiation protocols.

4.2.2 Management Tool. The management tool, an additional PC-based application, was developed for three main purposes (Figure 5(a)). First, it is used to initialize the UOS server, monitor its status, and track server availability and client connections. Second, the tool connects to a repository hosting platform where all files and the revision history of each file are stored in the cloud.

Third, the tool synchronizes global data, such as experimental setup details, Git repository data, and server conditions (e.g., status, client number). Additionally, for experimental control, we implemented a global clock that records the remaining experimental time and aligns the start and finish of all distributed clients.

4.3 Shared Visual Workspace

Based on ***DO1***, a shared workspace visualizes common maps for distributed users, aiming to create congruent VR interaction spaces across heterogeneous perspectives. An asymmetric virtual scene is applied for the Commander and the Field Responder to better align their spatial framework.

4.3.1 Role-Specific Workspace Design. Due to different spatial reference frames, the workspace design for the Commander and the Field Responder is different (Figure 7). For the Commander, a virtual table with a see-through layer (see Section 4.3.3) serves as the sketching workspace, aligned with the physical table with conformal geometry for passive tactile support and improved ergonomics [88]. An information card displays time and text to track the experiment phase and the remaining time. Virtual buttons along the sketching workspace provide functions such as eraser, save, pin placement, layer shift, and video control (exclusive to the Commanders). A video player, available only to Commanders, allows pausing and replaying drone footage. The workspace design for the Commander is shown in Figure 5(c).

For the Field Responder, the see-through layers are scaled down and attached to the non-dominant hand controller, while the virtual table is hidden. A virtual compass is placed near the layers to assist with navigation. To enhance awareness, we assign unique colors to each client.

4.3.2 Role-Specific Scene Perspectives and Locomotion. The Commander and Field Responder view the same virtual scene from different perspectives. The Commander is off-site and observes the scene through drone footage, whereas the Field Responder operates inside the building and performs navigation and search tasks. Locomotion is enabled only for the Field Responder, as shown in Figure 5(b). With the dominant hand controller, pushing the *Thumbstick* forward draws an arc raycast that indicates the target position and facing direction; releasing teleports the user to that position. Pushing the *Thumbstick* left or right rotates the user accordingly.

4.3.3 3D Map Representation through Layered System. The layered system is adapted from VResin [88] and has been shown to help sketch better interpretable maps for multi-layer buildings (Figure 5(c)). It uses the acetate sheet metaphor familiar to SAR responders that overlays sketched information on base maps. While a single layer is the same as a traditional 2D sketch on a flat surface, multiple layers serve as a mental scaffold for vertical representation. Users can customize the gap between layers to represent floor height. A layer shift button allows a change between layers. The layer on the tabletop is the active layer that a user sketches on. Cartographic elements (e.g., strokes, pins) [82] on the active layer are fully rendered, and inactive layers are displayed with low transparency. A layer management panel is provided in front of the layers, showing all layers. Users can change layers by toggling desired layers on the panel, and the corresponding layer will become the active layer. The active layer is highlighted on the panel, so the user can identify which layer is activated.

4.3.4 Reference Image of Layers. The user can customize the reference images (e.g., floor plan or site map) visualized as the texture of layers, as shown in Figure 5(c). The reference image anchors sketches to a common coordinate system for consistency between the Field Responder and Commander.

4.4 Externalization Tools for Spatial Communication

Based on ***DO2***, we provide a rich set of externalization tools that support line, point, and area annotations and can present multimodal information to support collective spatial cognition. Considering the complexity of the environment and its dynamic evolution, the interaction design strives to be as efficient and intuitive as possible.

4.4.1 Sketch-based Map Annotation. We provide multiple map annotation methods. Firstly, we provide surface sketch mapping for AOI. Considering the use cases of USAR, which primarily focus on *planar* information, such as danger zones. CoMap allows users to create closed curves to mark the AOI. Different colors or icons can be assigned or placed on closed curves to represent different types of AOI, as shown in Figure 5(e). Secondly, we provide freehand 3D sketch mapping, which enables users to lift their hands and sketch in mid-air to convey complex 3D information. The user holds the controller as a pen, presses the *Grip* button to start

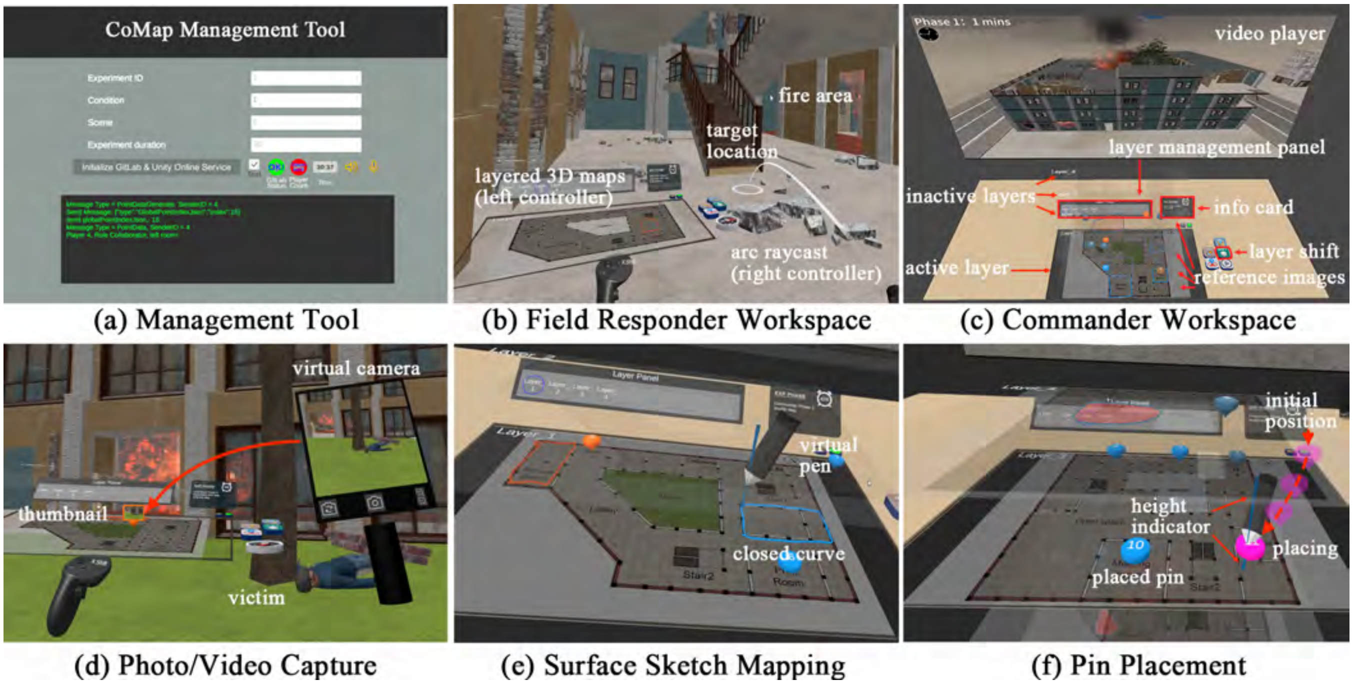

Figure 5: Core interfaces (a-c) and functions (d-f) of CoMap. (a) Interface of the management tool used for UOS server control, data logging, and global data synchronization. (b) The perspective from a Field Responder navigating the virtual scene using arc raycasting. (c) Key components of the Commander's workspace, including a layered system used for 3D map representation of a multi-level building, and a video player. (d) Multimodal communication through photo and video capture from the Field Responder's perspective. (e) Surface sketch mapping, where sketched curves are projected onto layers. (f) Interaction process for relocating a pin by dragging it from a corner to the desired position.

sketching a stroke, and releases it to finish. This feature allows users to make free annotations, which is particularly useful for line-based information, such as marking evacuation routes.

4.4.2 Pin Placement for POI. A pin, visualized as a "thumb tack," is used to mark POI. After pressing the pin placement button, a pin is generated at a predefined location (e.g., a corner) on the map. The user can then touch the pin using the controller and press the *Grip* button to drag it to modify its location. Figure 5(f) illustrates the process of pin placement. Different icons can be placed on the head of the pin to indicate various types of POIs. Pins can be placed in 3D to represent vertical information, with height indicators aiding in altitude perception between floors.

4.4.3 Multimodal Communication. CoMap integrates a real-time voice channel for rapid coordination between team members. Voice is used for quick clarification and handoffs, while the map serves as the persistent record. We use the built-in *Hello* service from UOS for low-latency multiplayer voice. Additionally, photography and video provide concrete visual context for on-site conditions. After creating a map element such as a POI or AOI, users can attach images or short videos. Attachments appear as thumbnails on the element, open in an in-scene viewer, and stay linked to the element during synchronization. Media can originate from drone footage on the Commander side or field-captured images from the Field Responder side, as shown in Figure 5(d). Thirdly, CoMap supports handwritten notes. Notes can be anchored to specific sketched elements and shared in the workspace.

4.5 Data Logging, Sharing and Reconstruction

Based on ***DO3***, we use GitLab [40] to create, store, manage, and share map data, leveraging its access control, task management, and continuous integration features.

4.5.1 Data Logging and Sharing. For prototyping and experimental purposes in this research, sketch mapping progress is stored via the Git version control system. At the beginning of the sketch mapping, the management tool (Section 4.2.2) created a Git repository on GitLab. Each client then clones the Git repository to their local device. The JSON file used for data synchronization is also used for data logging. The JSON file is added and committed to the local Git repository after each operation. At the end of the sketch mapping, all commits are pushed to the remote Git repository.

Verbal communication is recorded and saved to cloud storage. An open-source automatic speech recognition model (Whisper) [62] is then applied for speech recognition and auto-transcribed. We developed a Python script for segmenting long text passages and breaking them down into sentences. Then, the text is structured into a CSV file with index, start time, end time, duration, role of speaker, and content. The CSV file is stored in the remote Git repository after each operation for later analysis (e.g., to measure communication in Section 6.1.1).

4.5.2 Reconstruction Tool. Each Git repository contains files that store all the sketch processes of a sketch map. The JSON files contain a timestamp for each operation, which is then used to reconstruct the whole sketching process step by step for after-action review and debriefing. This can be useful for monitoring the search progression and prioritizing potential issues for planning and operation staff that support the Field Responder at a tactical level.

5 USER Evaluation

5.1 Study Design

To evaluate our prototype's effectiveness and usability in training newcomers, we conducted a within-subject study with participant dyads. The study employed a single-factor design with two conditions: (1) Baseline, emulating current practices, and (2) CoMap, representing the proposed system (see Table 2). Each dyad, consisting of one participant representing the *Commander* and one participant representing the *Field Responder*, experienced both conditions across two building scenes of equivalent architectural complexity (see Figure 6). The conditions and scenes were counterbalanced in full counterbalancing order to reduce order and learning effects. Participant roles within each dyad remained fixed throughout the experiment. The study protocol was approved by the IRB board of ETH Zürich.

5.2 Participants

We recruited 26 participants (13 women, 0 non-binary or self-described; aged 22–51, $M = 29$, $SD = 6.26$) forming 13 dyads. The participants were unfamiliar with each other, reflecting real-world scenarios in which volunteers often work with strangers [34]. This setup allowed us to stress-test the system performance under realistic collaboration conditions [71]. Since our tools are primarily aimed at training beginners, we recruit individuals with relevant professional backgrounds (such as GIS, cartography, architecture, structural engineering, or urban planning) who have extensive experience in orienteering and spatial thinking skills, and who are interested in serving as SAR volunteers. All had normal or corrected vision, were right-handed, and used their dominant hand for tasks. Compensation followed local hourly wage rates.

5.3 Storyline of the Game

The purpose of the game consists in training of coordination, mapping, and strategic decision-making for the early stage of SAR (e.g., find trapped victims, situation assessment). The game is not meant to perfectly mimic the realities of SAR (e.g., much like [80]), but does offer a time-constrained environment with activities similar to SAR. For example, SAR teams often work at an even pace, doing structural assessments and careful breaching; fire is not often a part of their work. At the same time, we aim to create a sense of urgency in the study, and so focusing on building search with fires helps to create this. Obviously, SAR search teams also do not teleport through space, but this design supports the usability of VR, particularly in minimizing motion sickness, in the study. The design is thus not *perfectly* ecologically valid, but is useful to offer insights into what the experience of using CoMap in a disaster context might be like.

We describe the storyline of the game using six key elements outlined by Macklin and Sharp [56], namely the playspace, the players, the objects, the actions, the rules, and the goals:

- ***Playspace.*** The scenario simulates a post-earthquake disaster in a multi-layer building with structural damage, trapped victims, and blocked routes due to fire hazards and collapsed sections. Prior spatial information (e.g., floor plans) is rendered obsolete. The design of the playspace is shown in Figure 6.
- ***Players.*** Two roles are involved: the Commander, with a strategic allocentric view, and the Field Responder, with an egocentric exploration view.
- ***Objects.*** Players interact mainly with the map and interface functions. The Commander can watch drone footage while the Field Responder can navigate inside the building. Both can access the building's original floor plans as baseline information.
- ***Actions.*** Drones assist in search, observation, and documentation [85]. The Commander uses drone footage to identify hazards and victims [44], while the Field Responder verifies POIs (e.g., victims) and AOIs (e.g., fire hazards) from within the building. Communication occurs via walkie-talkie, with the Field Responder requesting situational information about a particular area or to locate out-of-sight victims or hazards, and the Commander updating a tactical 2D/3D sketch map based on incoming reports and drone footage [8].
- ***Rules.*** Rules differ across experimental conditions (Table 2), mainly in terms of sketch mapping method, map visualization, and information access. The Baseline condition represents real SAR practice, where a Field Responder uses paper map annotations and communicates via radio. The CoMap condition integrates CoMap features to evaluate their effectiveness. The setup follows the recommendations of Machuca et al. [55] to minimize variability between systems in A/B evaluations.
- ***Goals.*** The joint goal is to complete a tactical sketch map that accurately marks the locations of the victims and delineates the areas affected by fire.

5.4 Materials

5.4.1 Stimulus. In order to approach RQ1, one of the authors, an architect, designed two buildings (as shown in Figure 6) with comparable layouts and floor areas for different conditions and designed a simple building for the tutorial. We captured the floor plans of the buildings as reference images and created their damaged version as stimuli. An exploded axonometric picture of victims and fires in building 1 can be found in Figure 1 left. For both stimuli, each floor included fire hazards, structural damage, and obstruction of access. One staircase was destroyed, requiring the Field Responder to detour to reach the upper floors. Large cracks in the exterior walls allowed the Commander to gain visual information from the outside. Falling walls in the building increased the visibility of both players. Victims were randomly

Table 2: The setup of baseline and CoMap conditions for a SAR game.

Features	Condition 1 (Baseline)		Condition 2 (CoMap)	
Role	Commander	Field Responder	Commander	Field Responder
Spatial frame	Allocentric	Egocentric	Allocentric	Egocentric
Sketch mapping	2D	N/A	3D	3D
Map view	2D	2D	3D (Layered)	3D (Layered)
Share maps	× (except initial map after Phase 1)	×	✓	✓
Can draw	✓	×	✓	✓
Verbal communication	✓	✓	✓	✓
Task (Phase 1)	Make initial map from drone footage	Explore surroundings	Same as Baseline	Same as Baseline
Task (Phase 2)	Update map from drone and reports	Search interior, report	Same as Baseline	Search interior, report, & update map

Figure 6: The design of the stimulus. The number of fire hazards, structural damage areas, broken staircases, and victims is consistent across both buildings. In the experiment, the Commander watches an orbiting drone-view video of the building while the Field Responder locomotes inside the building. The fire and damage areas, as well as the broken staircases, are impassable.

placed throughout the building; some were visible through cracks, while others could only be seen by the Field Responder player. In the tutorial, two victims were placed. One is in the atrium, which can be seen from the Commander's drone view, while the other is under the roof and can be seen by the Field Responder. A fire hazard is on the floor that can be seen by both players.

We used Unity (unity.com, a 3D game engine) to create digital models of these buildings. Orbiting drone-view videos were created to display the building from varying heights, with the drone's altitude transitioning from ground level to aerial perspectives.

5.4.2 Interfaces. We used Unity to develop interfaces and ensured a fair comparison by simulating both conditions in VR. We use Meta Quest HMD [59] to run the interfaces. To simplify the experiment, we restrict the externalization tools for surface sketch mapping for AOI, pin placement for POI, and voice communication in our user study. The Commander's content on the sketch map is colored blue, while the Field Responder's content is colored orange.

The experimental conditions differed in the map representation. In Baseline, we only provide one layer and a composite image of multiple floor plans as the reference image. This setting mimics traditional SAR settings, where physical maps are assembled manually. In CoMap, we provide four layers, and each floor plan is organized in each corresponding layer. Figure 7 shows the layered floor plans in the CoMap condition and the composite floor plan in the Baseline condition.

The body gesture differed between the Commander and the Field Responder (see Figure 7). The Commander remained seated, sketching on a tabletop while watching a simulated drone-view video in VR. They sketched on a virtual table aligned with the physical table in VR. In contrast, the Field Responder operated in a large open space, moving freely. In VR, they locomote using the non-dominant hand controller and sketched with the dominant hand controller in CoMap.

5.5 Procedures

The procedure is shown in Figure 8. Participants met each other, were welcomed, and were introduced to the study. Then, the participants were taken to separate rooms, each assisted by an experimenter. Experimenters communicated via an internal text-based chat platform to update each other on the status. The participants were then asked to complete a demographic questionnaire that also included an architectural spatial ability test [16]. The whole meet-up section took approximately ten minutes. Then, participants watched a role-specific instructional video, wore an HMD, and completed a training task with a simple building to familiarize themselves with the devices, interface, and interactions (approx. seven min). They then had three minutes to discuss strategies with each other via voice communication. Then, they played the SAR games and finished tasks described in Table 2. The game ended when time ran out (13 min). Then, both players took off the HMD and completed a post-condition questionnaire on their user experiences (Appendix B). This procedure was repeated in the other respective condition using the other building. Subsequently, participants were asked to complete a post-experimental questionnaire and complete a semi-structured interview on their preferences and experience (see Appendix C).

5.6 Data Collection and Evaluation Metrics

We adopted 13 metrics as dependent variables, summarized in Table 3. Data sources involved sketch maps (SM), voice transcriptions (VT) for communication behavior analysis, as well as quantitative and qualitative data from subjective ratings (SR) and semi-structured interviews (SI), enabling a comparison between CoMap and traditional mapping (i.e., baseline) approaches. These metrics were selected based on our review of SAR training, sketch mapping, and spatial cognition literature.

6 Results

Statistical significance was assessed using a two-tailed criterion of $p < .05$. When normality was violated, non-parametric tests (e.g., the Mann–Whitney U test and Wilcoxon signed-rank test) were employed; otherwise, parametric tests (e.g., the paired-samples t test) were applied. To solve the multiple comparisons, p-values were adjusted for false discovery rate (FDR) using the Benjamini–Hochberg (BH) procedure with a target FDR of 0.05, and are reported as p_{adj} values [15].

6.1 Quantitative Results

6.1.1 Communication Behaviour Analysis. Table 4 summarizes the distribution of the communication structure between conditions and roles. The percentages indicate the proportion of sentences in each structural stage relative to the total number of sentences. In terms of condition effects, both roles spent significantly more time in the D phase under CoMap ($p < .01$) compared to Baseline ($p < .001$). In contrast, participation in S phase was significantly higher in Baseline for both roles ($p < .01$).

Regarding role differences, commanders initiated more than field responders across both conditions—Baseline (M = 11.41% vs. 2.63%) and CoMap (M = 15.14% vs. 2.36%)—with both differences being significant ($p < .001$ and $p < .01$). Field responders described more than commanders in both conditions (all $p < .001$). In the S phase of Baseline, commanders engaged more than field responders ($p < .05$). For the C phase, commanders spent significantly more time than field responders in both Baseline (M = 7.23% vs. 1.59%, $p < .001$) and CoMap (M = 4.90% vs. 2.00%, $p < .05$).

The anticipation ratio did not show significant differences between the conditions (Baseline: $M = 3.61$, $SD = 1.64$; CoMap: $M = 4.92$, $SD = 2.96$). Both values are greater than 1, indicating that the team members effectively anticipate each other's needs and reduce the need for explicit requests under both conditions [30].

Communication effectiveness also did not differ; both conditions received high scores (5 out of 7 on the rating scale).

6.1.2 Sketch Mapping Analysis. The related metrics are illustrated in Figure 9. Participants drew AOI and POI approximately 25% (0.22 per minute) faster using CoMap than Baseline, $F(1, 24) = 7.75$, $p < .05$. For the map-accuracy POI and AOI analyses, p-values were BH-adjusted for multiple comparisons within each metric family. CoMap outperformed the Baseline on map accuracy (AOI) in terms of AOI IoU, $t(12) = 2.73$, $d_z = 0.76$, $p_{adj} < .05$, and completeness, $t(12) = 2.08$, $d_z = 0.58$, $p_{adj} < .05$.

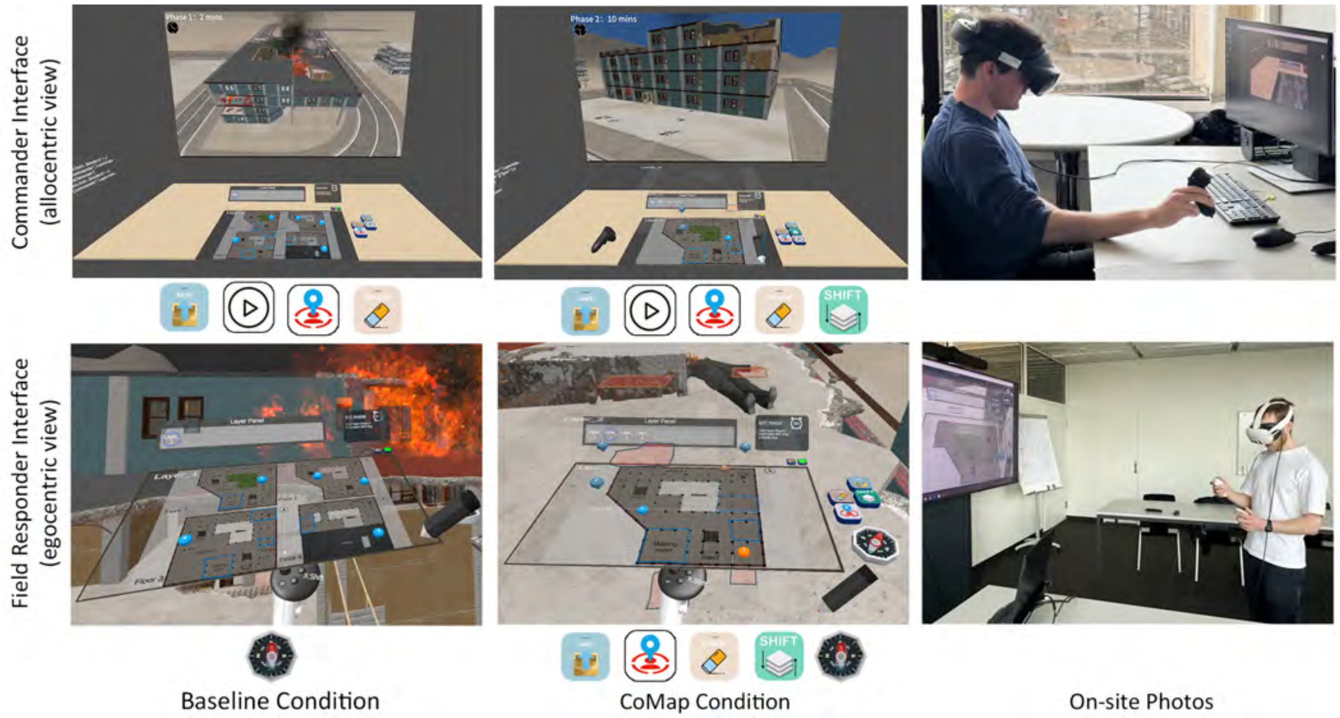

Figure 7: The interfaces for the Baseline, and CoMap from Commander's allocentric and Field Responder's egocentric perspective. Functions are listed below each interface, including Save, Video Play, Pin Placement, Eraser, Layer Shift, and Compass.

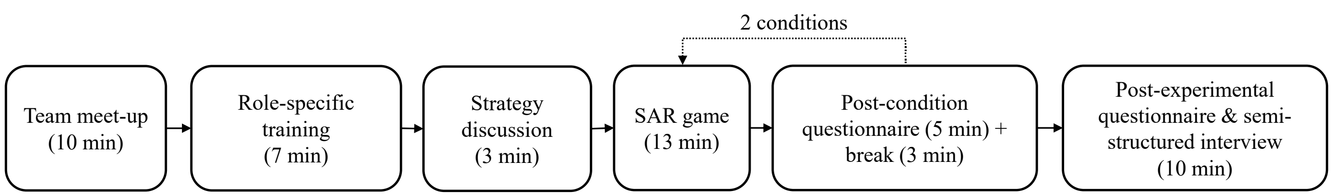

Figure 8: The procedure of the user study.

6.1.3 User Experience. Both interfaces received high scores in the social presence evaluation (Figure 10(a)) and SUS scores (Figure 10(b)). In self-rated usability (Figure 10(c)), CoMap was significantly lower on perceived interface limitations (PEQ-1; $F(1, 50) = 7.75$, $p < .01$) and higher on satisfaction with the resulting map (PEQ-2; $F(1, 50) = 5.70$, $p < .05$). For the SIM-TLX results (Figure 10(d)), mental demands were higher than physical demands, while high temporal demands may have contributed to increased stress. Distraction and perceptual strain remained low in both conditions.

6.2 Qualitative Results

This section summarizes comments from the post-experimental semi-structured interviews (Appendix C, SI-1 – SI-8).

6.2.1 User Preference. After experiencing both conditions, 65.4% of participants preferred CoMap, while 34.6% favored the Baseline for three main reasons. First, participants who preferred the Baseline emphasized its clear division of responsibilities. In contrast, CoMap required users to manage both sketching and reporting, which introduced multitasking challenges. Second, the Baseline's 2D map enabled users to view all floor plans simultaneously, but its lack of vertical information often required additional reasoning and interpretation efforts. CoMap's 3D map improved spatial orientation in multi-floor environments. As P1 noted, "*It is much easier to mentally locate the places in 3D.*" Third, while verbal communication in the Baseline was intuitive, it had a lower tolerance for errors. P4 (Field Responder) mentioned that saying "left" instead of "right" caused the partner's confusion. CoMap's shared visual workspace improved unambiguous spatial communication.

6.2.2 Communication Strategies & Patterns. Participants in Baseline spend more time on verbal clarification than on searching, reducing the efficiency of the task. In contrast, CoMap enabled participants to search faster through direct annotations, shifting

Table 3: Summary of evaluation metrics.

Measure	Metric	Definition	Range	Source
Communication behaviour	Structure analysis	Communication is divided into four stages [7]: Initiation (I), inquiring about spatial information or relevant aspects; Description (D), providing spatial details or explanations; Secure (S), clarifying or verifying information; Conclusion (C), concluding the exchange.	[0, 1]	VT
	Anticipation ratio	Ratio of unsolicited information provided to explicit information requested; higher values (>1.0) indicate proactive communication and effective coordination [30].	[0, 1]	VT
	Effectiveness [60]	Self-rating (Appendix B, PCQ-1).	[0, 7]	SR
Sketch mapping	Efficiency	Correctly drawn map elements per minute.	[0, ∞]	SM
	Completeness	Proportion of ground-truth elements drawn in the sketch map for both AOI and POI [88].	[0, 1]	SM
	Error rate	$1 - A/B$, where A is the correct elements and B is all drawn elements for both AOI and POI.	[0, 1]	SM
	AOI intersection over Union (IoU) [67]	Area of intersection divided by area of union between drawn and ground-truth AOIs.	[0, 1]	SM
	POI accuracy	Proportion of POIs placed within a threshold distance of ground truth [88].	[0, 1]	SM
User experience	Social presence	Items from Temple Presence Inventory (Appendix B, PCQ-2 to PCQ-4) [54].	[0, 7]	SR
	Usability	System Usability Scale (SUS) [18] and self-ratings (Appendix C, PEQ-1 to PEQ-4).	[0, 100]	SR
	Task load	Simulation Task Load Index (SIM-TLX) [38].	[0, 100]	SR
	User preference	Self-reported responses (Appendix C, SI-1 to SI-3).	[0, 7]	SI
	General feedback	Self-reported responses (Appendix C, SI-4 to SI-8).	[0, 7]	SI

Table 4: Structure analysis across conditions.

Condition	Role	Initiation (I)	Description (D)	Securing (S)	Closure (C)
Baseline	Commander	11.4%	32.4%	48.9%	7.2%
	Field Responder	2.6%	67.9%	27.8%	1.6%
CoMap	Commander	15.1%	59.1%	20.9%	4.9%
	Field Responder	2.4%	82.8%	12.9%	2%

focus from explanation to exploration. P5 (Field Responder) remarked, "*I focused more on myself and looked through all the rooms as fast as possible.*" The communication patterns are different: Baseline relied on one-way verbal confirmations and clarification. P4 explained, "*One strategy we developed was to reiterate the information to make sure it was correct.*" In contrast, CoMap supported bi-directional messaging with cross-validation through sketches and reports, reducing repetition and increasing efficiency.

6.2.3 Limitations Identified by Participants. Participants requested more powerful map manipulation features, including rotation, panning, and zooming. Additionally, they preferred displaying the field responder's real-time location on the map. Some field responders favored continuous walking over teleportation for movement, but teleportation was used to minimize motion sickness in our game.

7 EXPERT INTERVIEWS

To gather more feedback and assess the potential reception of CoMap in real-world SAR training and missions among our target users — practitioners in emergency and disaster response, we invited the same nine experts (E1-E9) who were interviewed in the formative study (Section 3) to evaluate CoMap. Each session included a 5-minute introductory session, where the interviewer presented the tool to the participants using a combination of interface images and background videos. This was followed by a 60-minute semi-structured interview designed to explore the

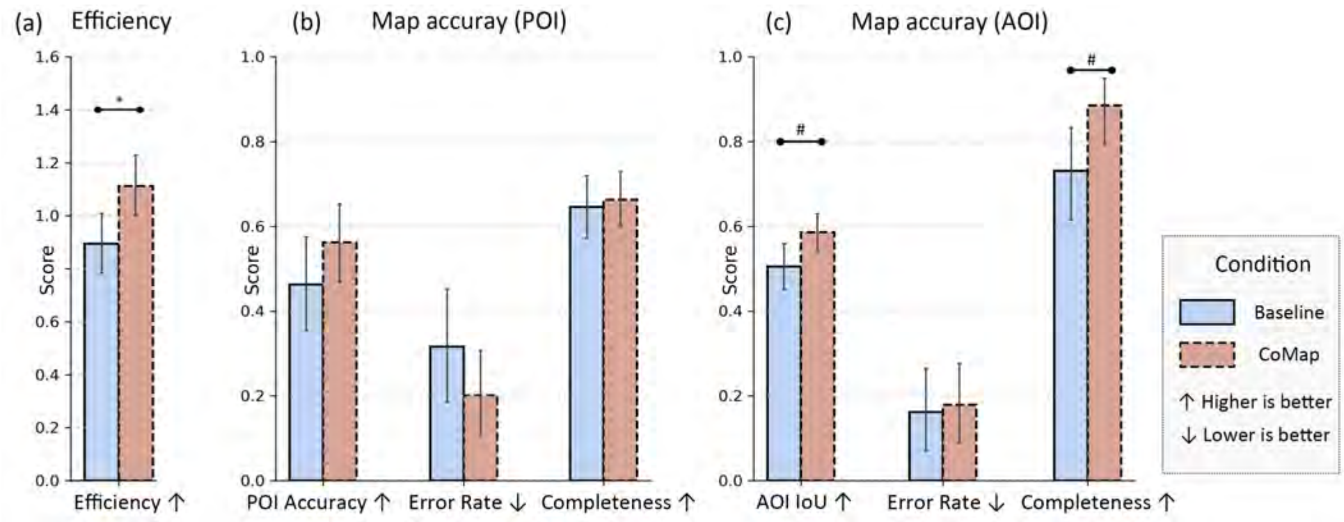

Figure 9: Bar plots of sketch mapping analysis. The error bars indicate the 95% confidence intervals. $* = p < .05$, $\# = p_{adj} < .05$.

impressions about CoMap, its potential utility in real-world SAR operations, comparisons with traditional tools, and suggestions for improvement. A complete list of interview questions is provided in the Appendix D. The study protocol was approved by the IRB board of *anonymized university*.

Participants expressed strong interest in adopting CoMap for SAR operations, noting its potential to enhance communication and coordination, and train transferable skills. At the same time, they identified several constraints and risks that need to be resolved for real-task deployment. Looking forward, they outlined key features that could strengthen the role of AR-powered SAR mapping. In general, our results are organized around three themes: perceived value, identified constraints, and directions for future improvement.

7.1 Perceived Value

7.1.1 Enhanced Communication Efficiency. Experts agreed that CoMap might improve communication within heterogeneous SAR teams by making complex 3D spatial information easier to convey and interpret. Its support for multimodal communication can strengthen shared situation awareness and collective spatial cognition, streamlined coordination, and allow for timely error detection and correction. For instance, E2 stated *"Map updates from field responders can assist commanders in understanding the situation more clearly."*

7.1.2 Training Transferable Skills. CoMap showed potential as a platform for scenario-based training, fostering transferable skills such as coordination, cooperation, and mutual understanding. These applications were seen as valuable for preparing heterogeneous teams to operate effectively under pressure before entering real-world missions. As E9 noted, CoMap could strengthen team coordination such that *"a simple gesture or glance should be enough to know what to do."*

7.1.3 Post-task Review and Debrief. CoMap's data logging and reconstruction functions could provide a basis for reviewing decisions, visualizing team allocation, and identifying coordination outcomes. This might support reflection, improve future practices, and provide evidence for post-incident analysis. For example, E7 believed that clear data logging is crucial for *"resolving disputes and clarifying responsibilities"* during debrief.

7.2 Identified Constraints

7.2.1 Data Constraints. Participants emphasized concerns about data reliability and completeness. Missing, delayed, or inaccurate input could reduce the quality of shared information. For example, E6 mentioned that *"even small defects can undermine trust and compromise decision-making in time-critical contexts."*

7.2.2 Technical Constraints. Limitations included hardware fragility and connectivity problems in extreme environments, as devices may fail under heat, smoke, dust, or unstable networks, affecting the ability of the system to respond to emergencies. E3 and E9 emphasized that *"the weight and size of the headsets were seen as practical barriers,"* restricting mobility and increasing strain. Questions also arose about the limited realism of simulations, which may hinder the transfer of training to practice. E9 cautioned that *"fire scenes are highly complex and unpredictable, and no simulation can fully replace real-world experience."*

7.2.3 Usability, Social, and Economic Constraints. Beyond technical issues, participants noted the multitasking burden on field responders and the risk of overreliance on technology, which could weaken judgment. E2, E5, and E7 also expressed doubts about social acceptance, while the cost of equipment and the learning curve, particularly for older or less experienced personnel, were seen as barriers to broader adoption.

7.3 Suggestions for Future Improvement

7.3.1 Intelligent Assistance. Related proposals included Intelligent Risk Filtering to reduce cognitive load, an AI-assisted Navigation Tool to propose adaptive routes in dynamic environments, and an

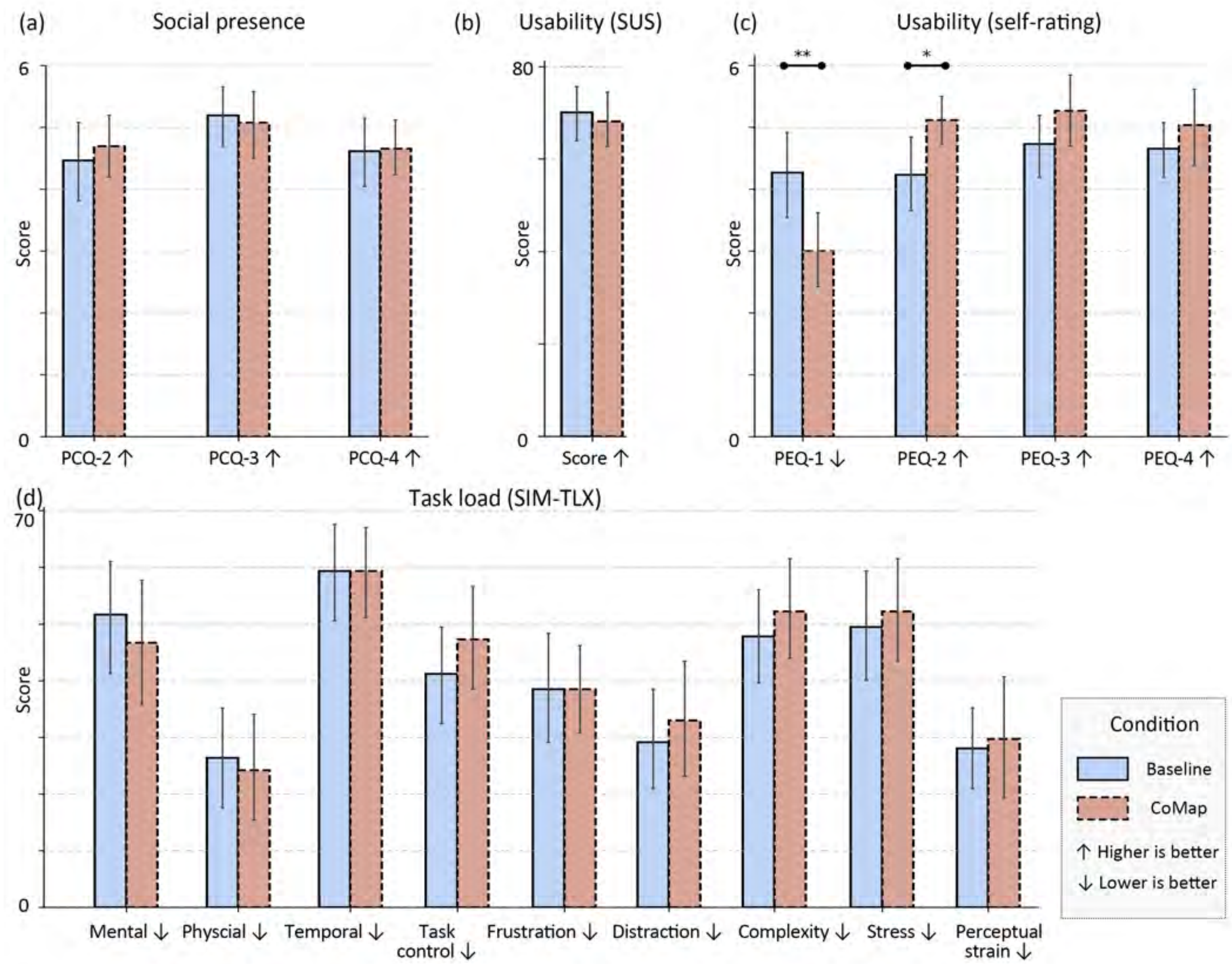

Figure 10: Bar plots of user experience analysis. The error bars indicate the 95% confidence intervals. $* = p < .05$, $** = p < .01$.

LLM-based Communication Tool to bridge language barriers in international teams.

7.3.2 Safety and Resilience Support. Related proposals included Wearable Sensors to track physiological states, Real-time GPS Positioning to improve situational awareness, and Mobile Relay Devices to sustain communication in adverse conditions.

7.3.3 Environmental Sensing. Participants highlighted Drone Integration for rapid area scanning and live updates, along with Thermal Imaging to detect survivors in smoke-filled or low-visibility contexts.

8 Discussion

In this section, we first answer our first two research questions with a summary of results from our controlled user study. We then synthesize findings from the controlled study and expert feedback to understand the potential of introducing 3D sketch mapping technology to SAR. Specifically, we compare sketching interactions (2D vs. 3D) and communication modalities (verbal vs. visual), followed by a discussion of the communication behavior of our collaborative 3D sketching system. Finally, we discuss limitations and future work.

We summarize our answer for each research question below:

RQ1. ***Does collaborative 3D sketch mapping enhance efficiency and accuracy, as well as user experience while reducing task load in SAR compared to conventional 2D sketch mapping?*** Regarding RQ1, our results show that collaborative 3D sketch mapping significantly improves mapping efficiency and AOI accuracy, as indicated by higher IoU scores and completeness. Participants reported greater satisfaction and experienced fewer interface constraints than with the 2D sketch mapping. The participants felt immersed and experienced some stress due to the complexity of the task and the time demands in CoMap, but not significantly compared to the conventional 2D sketch mapping condition.

RQ2. ***How does users' communication behavior differ between collaborative 3D sketch mapping and conventional 2D sketch mapping?*** Regarding RQ2, in 3D sketch mapping, participants in both Commander and Field Responder roles exchanged more spatial and contextual information while spending less time clarifying or confirming it compared with 2D sketch mapping. Users also showed greater proactivity in sharing information without prompting. This implies that collaborative 3D sketch mapping can better support collective perception and situational awareness.

8.1 2D vs. 3D Sketch Mapping

In intensive collaborative tasks like SAR, both the commander (or the liaison officer) and the field responders are iteratively taking the role of mappers and readers. From the mapper's perspective, they are typically more familiar with 2D sketch mapping, which is sufficient for single-story structures or outdoor scenes. However, 3D sketch mapping offers clear advantages in multi-story environments, enabling more accurate representation of vertical spatial relationships and the build of volumetric mental map. Despite this, it requires greater spatial ability to avoid errors such as misplacing elements between floors.

From the reader's perspective, 2D maps of multi-level spaces require mentally reconstructing and stacking floor plans, which increases cognitive load and error risk. In contrast, 3D sketch maps are more intuitive to interpret, particularly for vertical information, supporting faster comprehension and decision-making in time-critical scenarios. The combination of 3D cognitive maps of disaster scenes and rapid externalization by sketching highlights the potential of 3D sketch mapping as an effective communication method in the context of SAR.

8.2 Verbal vs. Visual Communication

8.2.1 Impact of Spatial Complexity on Communication Effectiveness. We found that users leveraged verbal and visual communication interchangeably, with each modality offering distinct advantages and limitations. Verbal communication was sufficient in simple environments or when users shared a standardized spatial vocabulary [79]. However, as spatial complexity increased or environments became more dynamic, verbal descriptions alone are prone to errors [48]. Thus, visual communication was essential for conveying complex spaces that are difficult to express through words, enhancing mutual understanding.

8.2.2 Synchronous vs. Asynchronous. Verbal communication is inherently dynamic and synchronous, unfolding in real time and requiring immediate feedback (e.g., back-channeling [79]) to ensure understanding [20, 48]. However, a noisy and chaotic environment and unstable signals at disaster sites often interfere with this feedback, resulting in frustration, missed messages, and communication inefficiencies. These features offer greater flexibility in distributed coordination, offering higher bandwidth for information exchange.

8.2.3 Nonstructural vs. Structural. Verbal communication, while efficient in face-to-face interactions, has an unstructured and ephemeral nature that makes it more difficult to archive and retrieve than visual communication. Although verbal language can be recorded and transcribed, Segal [73] noted that transcribed utterances often lack interpretability without access to the situational context. In contrast, visual communication is inherently more structured, persistent, and shareable, making it well-suited for distributed collaboration.

8.3 Communication Behavior using Collaborative 3D Sketch Mapping

Collaborative 3D sketch mapping can bridge the individual and collective mapping difficulties [4] that are limited by current geographic information systems (GIS), and enabling the overlay and updating of information on maps [32] fosters communication strategies that leverage the complementary informational asymmetries between command and field teams.

In the CoMap condition, participants exhibited more collaborative and descriptive communication than in Baseline. Phase D increased for both roles, reflecting improved situational awareness and articulation. Shared visual workspaces reduced the need for explicit confirmations (phase S), which was replaced by implicit visual cues. Initiation (I) behavior also increased, with commanders more frequently querying location and status (e.g., "*Is the fire north of stair one?*"), reflecting their active role in managing collective spatial cognition.

Qualitative feedback confirmed that collaborative sketch mapping enabled implicit coordination and reduced verbal burden. Participants reported that the combination of visual and verbal feedback accelerated decision-making and helped maintain focus on core tasks. The shared workspace supported real-time validation, enabling bidirectional messaging. This visual grounding shifted communication from linear, confirmation-heavy dialogue to more adaptive and efficient multimodal interaction. This even facilitates new communication and coordination patterns. For example, the commander may sketch a rough outline and then have it refined or confirmed by the field responder.

9 Design Implications

Through user study and expert interviews, we gained actionable insights into the design of collaborative sketch mapping tools for SAR training. Consistent with Alharthi et al. [4], our results underscore the role of map-based interaction in supporting collective spatial cognition and communication. Our findings highlight key design tensions and challenges in using collaborative 3D sketch mapping for SAR training. Building on this, we propose design implications for the software and hardware of future SAR tools which answer **RQ3.** ***How does users' communication behavior using collaborative 3D sketch mapping inform the design of future sketch mapping tools for SAR training?***

9.1 Software Design Implications

9.1.1 Integrating Multi-modal Spatial Communication. Different communication modalities serve distinct but complementary needs in SAR (e.g., Figure 11(a)) [3, 4, 80]. 2D maps provide clear overviews

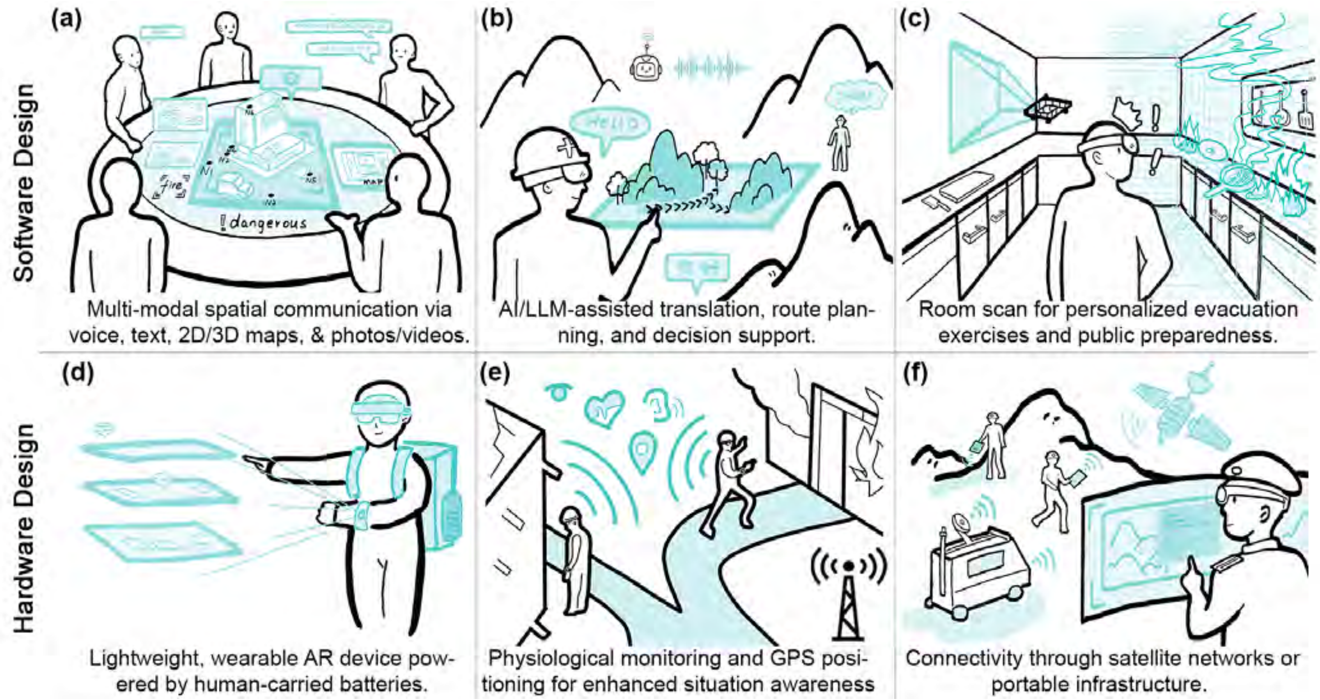

Figure 11: Software and hardware design implications. Illustration by an artist.

for rapid decision-making, yet they are limited in representing vertical space. In contrast, layered 3D maps allow for intuitive interpretation of spatial arrangements but may overwhelm users. Similarly, verbal communication is fast and intuitive but error-prone [79]. AI or LLM voice assistance, *if* proven to be safe, fast, and ethical, could be integrated for environmental perception, risk filtering, route planning, and decision support (e.g., Figure 11(b)). In contrast, visual communication (e.g., sketch mapping, photography, videography [8, 43]) is persistent and easy to interpret but may cause users to neglect reporting updates explicitly. In short, future systems should therefore support seamless transitions between 2D and 3D map representations (extending [3]), enabling fluid shifts in perspective, while also coordinating verbal and visual inputs through shared, synchronized workspaces. This integration would improve situation awareness and strengthen collaboration in complex SAR operations.

9.1.2 Multi-Scenario Training for Professionals & the Public. VR-driven simulation can complement existing SAR drills by recreating diverse disaster scenarios [5]. Unlike conventional evacuation or live exercises, immersive simulation enables systematic variation of conditions and repeated practice without physical risk, while maintaining transferability to real operations [19]. Representative training modules include high-rise evacuation, where blocked corridors, disabled elevators, or damaged stairwells block escape routes across multiple floors; victim search in collapsed structures, requiring navigation through unstable environments to locate and rescue survivors; hazardous chemical safety training, designed to prepare responders to handle, identify, and react to dangerous substances during industrial or laboratory spills and leaks; and multi-team coordination, where fire brigades, medical units, and drone operators must collaborate and allocate tasks efficiently under pressure. Beyond professional applications, such simulations can also support public preparedness. For example, individuals can digitize their own homes to rehearse earthquake response, conduct fire drills, practice shelter-in-place procedures during extreme weather events, or simulate nighttime evacuations during power outages, thus strengthening community awareness and resilience (e.g., Figure 11(c)).

9.1.3 Toward Higher-Fidelity Simulation. Simulation fidelity can run along multiple axes, aiming to replicate cognitive, functional, emotional, physiological, physical, etc. challenges of real emergencies [27, 36, 81], where simulation fidelity is placed improves skills along that axis [58]. Our interface design illustrates that VR has huge potential to achieve high cognitive and functional fidelity and, to some degree, capture emotional and physiological responses in users. To ensure that training in VR settings is more generalizable to real-life problems, helping users to build skills in managing cognitive workload and emotional and physiological stress, future systems can employ the following strategies to introduce stressors as needed: (1) simulating disaster chaos by integrating dynamic environmental elements such as visual smoke occlusion, fire spread, and virtual smoke propagation [58]; (2) introducing social stressors by increasing role diversity or making participants aware that their decision-making is being monitored and evaluated [17, 81]; (3) enhancing sensory stimulation to create situational pressure through visual effects (e.g., flickering flames, flashing emergency lights), auditory effects (e.g., alarms, explosions), haptic feedback (e.g., force-feedback equipment to simulate walls, shaking for earthquakes), and environmental realism (e.g., heated, smoke-filled spaces) [12, 53]; and (4) increasing task complexity and cognitive load by requiring participants to manage concurrent objectives and solve challenging problems [5, 77, 81]. In addition to stress-induction techniques, our experimental findings highlight the importance of achieving high functional fidelity to support realistic decision-making processes, interactions, and team dynamics to ensure effective knowledge transfer.

9.2 Hardware Design Implications

While collaborative 3D sketch mapping shows promise for SAR training and potential field deployment, its practical use remains dependent on continued AR/VR hardware advancements. In line with the vision outlined by LaLone et al. [50], future AR-supported systems should emphasize durability, extended battery life, and reliable near-real-time data synchronization. This could be enabled by lightweight, wearable AR devices (e.g., wrist- or head-mounted) powered by human-carried batteries and built to withstand harsh SAR environments (e.g., Figure 11(d)). Physiological monitoring and GPS positioning should be integrated for status awareness (e.g., Figure 11(e)). Connectivity through satellite networks or portable infrastructure (e.g., tethered balloons, satellite-gathering vehicles) would further support robust data transmission (e.g., Figure 11(f)). These developments may enable CoMap to evolve from a research prototype into a deployable SAR tool, bridging experimental validation and real-world application.

10 Limitations and Future Work

We believe that the present study's focus on collaborative sketch mapping methodology, along with the design implications presented in Section 9, provides a foundation for future research in this domain. We have also outlined several challenges of our research and proposed directions for future work to address these challenges and extend the applicability of our system.

First, our VR training simulation does not fully replicate the range of stressors encountered in real-world , in-line with prior selective simulations (e.g., [77, 81]). In our experiment, we primarily induced time pressure through countdown indicators, strict temporal constraints, and a high number of simulated victims. However, we did not incorporate dynamic environmental changes – such as fire propagation or structural collapse – which are known to elicit heightened anxiety or panic. Future research should consider adopting a broader array of stress-inducing techniques to enhance the generalizability and realism of VR training, as described in Section 9.1.3.

Second, our experimental setup simplifies the complexities inherent in real-world SAR operations. Specifically, we focused on cartographic interactions and limited communication modalities – primarily sketching and reporting – thereby excluding the range of multimodal communication channels within our interface. Additionally, our two-role paradigm simplifies real-world SAR hierarchies. For example, in the context of the USA, incident command structures can involve a single commander with some fielded teams, or grow to be large and complex [1, 77, 79] . Our streamlined setup was designed to reduce participant fatigue, flatten the learning curve, and facilitate experimental control. Future research should explore more complex multi-role SAR simulations, which would introduce higher fidelity simulation around communication streams and coordination among participants. Studies could also benefit from longitudinal designs to evaluate how different communication and mapping methods perform over time and under more realistic conditions.

Third, our evaluation of CoMap was limited to fire-based scenarios, and we did not assess its applicability across other common incidents. Although the system's layered 3D map representation has demonstrated effectiveness in multi-story building environments [88], its utility may diminish in wilderness search-and-rescue (WSAR) operations. Scenarios such as locating missing persons in mountainous terrain, assisting injured individuals on remote slopes, managing cave rescues, or conducting post-avalanche searches present needs for 3D terrain models that may provide more appropriate and actionable spatial representations [87]. Future research can aim to evaluate CoMap's adaptability across a broader range of urban search-and-rescue (USAR) contexts, such as floods, structural collapses, or active shooter situations; in these built-environment scenarios, CoMap is reasonably suited already. To further enhance CoMap's generalizability, novel 3D map representation systems that integrate topographical data, elevation profiles, and geospatial features specific to WSAR can be developed.

Fourth, we acknowledge that while the current Git-centric data logging implementation functions effectively in controlled training environments, it may encounter significant limitations in real-world SAR deployments, where communication infrastructure is frequently degraded and cloud services may be inaccessible [51]. Although our locally stored, asynchronously buffered sketch maps can support continued data logging and expedite synchronization once connectivity is restored, they do not address the fundamental issue of network unavailability. To overcome this limitation, future implementations could incorporate a rapidly deployable system to re-establish connectivity [45] , along with a resilient and secure data logging and sharing infrastructure (e.g., edge computing [72] and delay-tolerant networking [39, 84]) to ensure robustness under post-disaster conditions, as indicated in Section 9.2.

11 Conclusion

This paper presents CoMap, a collaborative 3D sketch mapping tool for enhancing communication in SAR training. In a user study with 13 pairs, CoMap outperformed conventional 2D sketch mapping in mapping efficiency and accuracy, while maintaining comparable task load and communication effectiveness. Participants reported higher satisfaction and fewer interface constraints. Communication analysis revealed more proactive information through rich exchanges with fewer clarification requests. We also interviewed nine SAR professionals to generate our design objectives and evaluate CoMap, who confirmed its value for training and coordination, while highlighting concerns about hardware reliability and operational deployment.

Based on these findings, we outline the design implications for future SAR tools: (1) realistic and multi-scenario simulation; (2) integrating multi-modal spatial communication; and (3) ruggedized, connected hardware for use in extreme environments. Although current technologies limit real-world deployment, CoMap offers a promising direction to advance collective spatial cognition, coordination, and decision-making in future SAR operations and training.

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A Formative Study Materials

A.1 Screening Survey (SS)

Part 1 – Participants Information and SAR Expertise

SS-1 Email:________; Gender:________; Age:________
SS-2 Role in SAR: [Commander / Field Responder / Both / Other]
SS-3 SAR service years: ________
SS-4 How would you rate your overall SAR experience?
SS-5 Can you briefly describe your primary responsibilities?
SS-6 What types of SAR missions have you been involved in?

Part 2 – Availability

SS-7 What times are you typically available for an interview?
SS-8 Do you have any additional comments?

A.2 Interview Protocol

Part 1 – Use of Map Technologies (M)

M1 Have you received training in reading or annotating maps?
M2 How are the following map types used in your SAR work? (Paper maps, GNSS devices (e.g., GPS), GIS software, web/mobile maps)
M3 What geographic data are most valuable during SAR operations? What useful data are typically missing?
M4 What challenges have you faced with current maps?
M5 How could map tools (e.g., collaborative mapping) be improved to better support SAR operations?

Part 2 – Communication and Coordination (C)

Questions for both roles:

C1 How do you communicate with other team members?
C2 What communication challenges have you encountered?
C3 How can advanced map tools (e.g., collaborative mapping) better support coordination and communication?

Additional questions for commanders:

C4 How do you share ideas or plans with other commanders?
C5 What is your typical process for making decisions?
C6 What factors influence your decisions the most?

Additional questions for field responders:

C4 How do you coordinate with other field responders?
C5 What do you need most to perform your tasks effectively (e.g., real-time data, instructions from commanders)?

B Post-condition Questionnaire

The post-condition questionnaire (PCQ) included two standardized instruments—SIM-TLX [38] and SUS [18]—along with four custom items on spatial communication (PCQ-1) and social presence (PCQ-2 to PCQ-4). All custom items were rated on a 7-point Likert scale for both conditions.

Spatial communication effectiveness

PCQ-1 How do you assess your ability to exchange spatial information with the given communication medium?

Social presence

PCQ-2 How often did you feel that your experiment partner could also see/hear what you were experiencing?
PCQ-3 To what extent did you feel that you could interact with your experiment partner?
PCQ-4 Seeing and hearing a person via a medium constitutes an interaction with him/her. How much control did you feel you had over the interaction with your experiment partner?

C Post-experimental Questionnaire and Semi-structured Interview

The questions in Part 1 were rated on a 7-point Likert scale to assess the user experience in both scenarios. The open questions in Part 2 were designed to gather user preferences and general feedback.

Part 1 – Post-experimental Questionnaire (PEQ)

PEQ-1 I felt limited by the interface in achieving the goals of our team.
PEQ-2 I am satisfied with the resulting sketch map.
PEQ-3 I could see using this interface or medium in search and rescue training/operations.
PEQ-4 I felt the interface or medium was easy to use for achieving our team's goals.

Part 2 – Semi-structured Interview (SI)

SI-1 Which experimental condition do you prefer?
SI-2 If you chose Baseline: Was verbal communication sufficient or even more efficient than 3D sketching? Why?
SI-3 If you chose CoMap: In what situations did you find this tool especially useful? Why?
SI-4 How did your strategies differ between the two conditions? What influenced your choices?
SI-5 How often did you need to improve new strategies? What challenges did you face?
SI-6 Did you feel that you understood each other's situation and action plans?
SI-7 Are there any features you suggest to improve?
SI-8 Anything else you would like to share?

D Expert Interviews Protocol for Tool Evaluation (T)

T1 What are your initial impressions of this tool?
T2 Do you see the potential for this technology to support real-world SAR operations?

T3 Compared to traditional map tools, what are the strengths and limitations of this system?
T4 In what scenarios would 3D sketch mapping be more useful than 2D mapping?
T5 What features or capabilities would you expect in a fully developed version?
T6 Do you have any concerns about using this system in practice (e.g., usability, training, compatibility)?
T7 What improvements or changes would you recommend?
T8 Is there anything else you would like to share?