I See You: Examining the Role of Spatial Information in Human-Agent Teams

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Awareness, and specifically, spatial awareness, has long played a pivotal role in Computer-Supported Cooperative Work research in both theory and design. This significant background gives awareness the ability to answer challenges facing human-agent teams in communication and shared understanding. As such, the current study investigates the effects of spatial information level (low, high) on the development of team cognition and its outcomes in varying compositions of human-agent teams (human-human-agent, human-agent-agent) versus human-only (human-human-human) teams. The mixed-methods study had teams complete several rounds of the NeoCITIES emergency response management simulation and complete various team cognition and perception measures, followed by qualitative free-response questions. The study found that human-only teams did not perform at the same level as human-agent teams, with multi-agent human-agent teams having the best performance. A significant interaction, though with inconclusive simple main effects, displayed the trend that human-agent teams had better team mental model similarity when spatial awareness was high rather than low, while human-only teams experienced the reverse trend. Qualitative findings identified that high spatial awareness jump-started team cognition development, fostered more accurate shared mental models, enhanced the explainability of the agent, and helped the iterative development of team cognition over time.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; Interaction techniques;

Additional Key Words and Phrases: team cognition, human-AI teaming, spatial information, artificial intelligence, human-AI interaction, shared mental model

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1 INTRODUCTION

The concept of awareness has been a hallmark of Computer-Supported Cooperative Work (CSCW) research for decades [33]. This research has been integral to the design of technology for cooperative work [33, 36, 37]. The definition of awareness within a CSCW context centers around understanding

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what others are doing, why they are doing it, and how this relates to their activities [23, 33]. Therefore, prior research has shown that awareness plays a crucial role in how teamwork is perceived and performed [24, 38]. Consequentially, improving awareness has also been considered an effective way to improve design for collaborative technologies supporting teamwork [33, 79]. Collectively, these studies have created various information models that work to support awareness. Specifically, *spatial awareness* models as they show promise in supporting distributed teams, which are incredibly common in the modern workforce [33, 86]. Spatial awareness is a specific model of awareness that exemplifies the awareness of one another but is managed through a spatially accurate medium that contains representations of the individuals [33, 41].

Furthermore, specific contexts of awareness, such as spatial awareness, have demonstrable effects on *team cognition*, a critical component of effective teams [37]. Team cognition is a construct referring to a collection of related concepts like team decision making, team situational awareness, team perceptions, and shared mental models [16], each based upon individual teammates' beliefs, expectations, and perceptions [49]. In this sense, the concept of team cognition draws significant parallels to awareness, with specific contexts of awareness like spatial and collaboration awareness showing strong similarities [37]. Consequentially, awareness is essential to establishing effective team cognition, making awareness and team cognition crucial components to effective teaming and collaborative technology development. From a design perspective, this linkage has resulted in collaborative technologies that convey factors of awareness like identity, intention, and location, which enhance the development of effective team cognition over time [13, 37].

As artificial intelligence (AI) technologies continue to advance rapidly, making human-agent teaming a reality [67], team research must address the importance of awareness in modern teamwork in a new context. However, human-agent teams face particular challenges in properly establishing awareness, echoed in recent CSCW research [108]. For instance, human-agent teams face significant human to agent communication difficulties [48, 91], complications in trust development [64, 66], and generally negative perceptions towards agent teammates [100, 108]. Additionally, these obstacles are only exacerbated by the introduction of additional agent teammates to the human-agent team [68, 73]. Given human-agent teams' communication deficiencies, their level of awareness and team cognition is significantly hampered. This limitation makes research on alternative means of developing awareness and communication through spatial mediums vital. Establishing awareness will help alleviate these challenges by fostering team cognition development in human-agent teams, supporting explainable AI, and enabling unique communication channels.

Nevertheless, existing CSCW work on awareness in teamwork has historically centered around human-only teams. Given the novelty of human-agent teams, the effects of awareness, specifically spatial awareness, on team effectiveness, team cognition, and design requirements have yet to be empirically explored. The following research questions address these gaps in the literature outlined above. Specifically, targeting the role of spatial awareness in developing team cognition in human-agent teams of varying composition as well as in human-only teams, and how spatial awareness impacts the outcomes related to team cognition:

RQ1: *Is the role of spatial awareness in team cognition development different for human-agent teams compared to human-only teams?*

RQ1.1: *Is the role of spatial awareness in team cognition development influenced by the number of agents in human-agent teams?*

RQ2: *Does spatial awareness influence the outcomes of team cognition (i.e., team performance, perceived team cognition) similarly in human-only teams versus human-agent teams?*

RQ2.1: *Does spatial awareness influence the outcomes of team cognition differently depending on the number of agents in human-agent teams?*

The current study answers these research questions through an empirical mixed-methods study with two conditions of spatial awareness and three conditions of team composition. Each condition completed four rounds of the emergency response management simulation NeoCITIES [46]. This study illustrates the quantitative and qualitative effects of spatial awareness and team composition on various interactions within teaming, including team cognition's development and its outcomes.

This work contributes to the field of CSCW in three key ways: (1) advancing the emerging field of human-agent teaming within the context of CSCW by exploring the relationship between spatial awareness and team cognition development in human-agent teams; (2) extends existing CSCW literature on what factors of awareness in distributed teams influence varying compositions of human-agent teams and human-only teams; and (3) providing valuable design recommendations to practitioners of human-agent teams seeking to establish effective awareness and team cognition in applied fields like advanced manufacturing and city management [80, 93].

2 RELATED WORKS

2.1 Perception and Communication in Human-Agent Teams

Current and recent technological advances in AI have resulted in the possibility of human-agent teams [32, 80, 97]. Human-agent teams involve at least one human working with at least one AI that has a level of autonomy that allows it to be considered a teammate rather than a servant [19, 67, 69, 75]. Though much is understood about teamwork for human-only teams, human-agent teams are nascent and have garnered significant research interest in the CSCW, and HCI communities [47, 53, 78, 101, 102, 108].

Though many comparisons can be made between human-only teams and human-agent teams [67], communication in human-agent teams can be particularly challenging [48, 91]. As agents gain higher levels of autonomy and decision-making capabilities, it is increasingly necessary for humans to be able to discern agent intentions to support mental models and trust [91]. A human-autonomy teaming literature review recently revealed that effective information sharing was a strong commonality amongst human-only teams that outperformed human-agent teams [80]. While technological advancements have been made in the field of natural language processing [6, 59], the natural language capabilities of AI systems do not yet meet the level required for human-agent teaming [107]. Alternatively, nonverbal communication has shown great promise as a communication style in human-agent teams. For instance, humans perceive agents that use implicit communication in human-agent teams more positively [53]. In a qualitative esports study, results indicated that some players would prefer to be able to communicate verbally but acknowledged that non-verbal communication (e.g., pings, visual markers) might be more realistic and valuable when teaming with an agent [108]. Meanwhile, other researchers have addressed agent communication shortcomings by increasing agent transparency to support the human's situation awareness [91], trust, and performance [69].

Regardless of an agent's task abilities and communication capabilities, a huge obstacle to overcome in human-agent teaming is the human's perceptions of the agent(s). Based on people's previous experiences with AI, human teammates might perceive the agent as only a tool and could be unwilling to team up with it [108]. This finding is especially prevalent in studies that utilize the Wizard of Oz protocol, where agent abilities match that of a human teammate to isolate perceptions of the agent. First, a study involving a ship training simulator revealed that humans who believed they were teaming with an autonomous partner gave their partner a worse affect rating and communicated significantly less [100]. Second, a study utilizing a remotely piloted aircraft simulation found that when humans believed that their teammate was an agent, they had more difficulties planning for and anticipating teammate needs [20]. Third, a study using human confederates acting as agent teammates revealed that humans have a more challenging time participating in implicit coordination, nonverbal communication, and team cognition when they perceive two agent teammates as compared to a single agent teammate [73]. Thus, being outnumbered by agent teammates and even simply perceiving that a teammate is an agent can interfere with critical team processes.

Based on the above-researched shortcomings of human-agent teams (i.e., verbal communication and agent perceptions), it is crucial to investigate human-agent teams further, how they differ from human-only teams, and how awareness and team cognition can affect them can be developed and supported in such teams.

2.2 Awareness and Team Cognition in Distributed Teams

The concept of awareness is of great importance to the CSCW community; however, the term itself necessitates clarification [33, 95]. CSCW researchers often agree upon a broad definition for awareness as "an understanding of the activities of others, which provides a context for your own activity... [which] allows groups to manage the process of collaborative working" [23]. Though this definition is suitable as a starting point, the need to pair the term with a descriptive adjective (e.g., collaboration awareness [50], workspace awareness [34, 38], mutual awareness [4], etc.) indicates that the term *awareness* alone lacks a needed level of specificity [95]. To focus this term and to assist with awareness in virtual spaces, many CSCW researchers have shown support for describing awareness with relation to the spatial model [33].

The spatial model is helpful for applications in which points of interest (e.g., people, information, artifacts) can be regarded as having position and orientation across which space can be measured [5, 89]. The spatial model is composed of several abstractions, including medium (where interactions occur), aura (properties of an object that enable interaction), focus (how aware you are of an object), nimbus (how aware the object is of you), and adapters (tools or objects that can modify aura, focus, or nimbus) [5, 33]. Spatial representations supporting high degrees of spatial awareness can exist in 2D (e.g., radar views and overviews to represent a workspace) and 3D forms (e.g., teammate avatars) [27, 37]. An example of spatial awareness supported by 2D representations is in tasks like distributed emergency management planning where shared maps act as spatial awareness information for teams [10, 13, 14].

Research has consistently provided evidence that supporting spatial awareness improves distributed team outcomes [34, 35, 77]. However, much can still be learned regarding how perceptions of teammates impact awareness. For example, a prior spatial awareness study showed that team members changed their communication when they met their teammate in a virtual room [22]. This study resonates with a more recent case study that emphasized the importance of perceptions of teammates and shared intentionality [99].

Importantly, awareness is also critical to teamwork in that it supports the development and process of *team cognition* [37] which has a well-researched relationship to team performance [18, 62, 65, 88] as well as other team processes such as coordination [26] and decision making [45]. Team cognition is an active cognitive team process [15] and is often measured by the degree to which team members have a shared understanding or shared mental model (SMM) [12, 17]. SMMs have been defined as "an organized understanding or mental representation of knowledge that is shared by team members" [61] and are often organized into the categories of task-related SMMs (e.g., equipment, task procedures) and team-related SMMs (e.g., roles, teammate skills) [62].

A major benefit of developing team cognition in CSCW is to support implicit nonverbal communication. Implicit nonverbal communication can involve interpreting objects in joint work [83] or observed actions [99]. Gergle (2014) noted that "action replaces explicit verbal instruction in a shared visual workspace" [30]. Being able to interpret objects and actions to better coordinate is well-documented in the teamwork literature. For instance, research has found that teams that develop SMMs or team knowledge can better implicitly communicate [15, 16]. As teams gain common ground, they can more efficiently communicate [11], which is especially valuable in fast-paced or stressful team environments. For instance, qualitative research involving esports players has consistently revealed the importance of implicit communication [56, 74]. The fast-paced nature of this context requires players to be able to see the behaviors of their teammates and predict their next actions while limiting the verbal communication overhead [74].

However, the development of and participation in team cognition does not come freely and is challenging for human-agent teams, which are significantly less likely to perceive team cognition than human-only teams [68]. Team cognition is heavily reliant on factors such as communication [40, 57], awareness [37], experience [42], and perceptions of teammates [85]. Noting that a benefit of team cognition is a reduction in the need for verbal communication [15, 16], while also acknowledging that communication is required to develop team cognition [40, 57] creates a challenging "chicken or the egg" dilemma for human-agent teams that often exhibit verbal communication challenges [20, 67, 80]. The challenge of supporting team cognition in human-agent teams is exacerbated when human perceptions of the agent create an additional impediment [20, 73, 100, 108]. Thus, it is useful for human-agent teams to rely on other team cognition support mechanisms such as experience, or more relevant to this study, awareness and nonverbal communication.

2.3 Creating Awareness in Impoverished Communication Environments

Communication plays an essential role in both CSCW [76, 82] and teamwork [16, 57]. Designing for nonverbal communication is particularly important in computational environments as it promotes richer interpersonal communication (e.g., telehealth [25] and social VR [58]), while also supporting essential teamwork functions [16]. However, teamwork in human-agent teams can be considered an impoverished communication environment due to challenges humans face in verbally communicating with agents [20, 67, 80].

Though human-agent teams might struggle to communicate verbally, these teams can still utilize nonverbal communication to support spatial awareness, and thus team cognition [40]. Explicit nonverbal communication is direct communication that might involve gestures [83] or annotations [106]. Research has revealed that making map annotation tools available to players can increase both actual and perceived performance while reducing frustration [1]. Further, players used these tools more often when the annotations were visible in the game world in addition to just being visible on the map [1]. In addition to annotations, many popular esports games allow for players to make *pings*, which are map or world animations to indicate a point or event of interest [51, 106]. The amount of pings has been found to have a positive relationship with player performance [51]. Thus, understanding how players use pings, annotations, and other nonverbal awareness cues is essential to supporting communication and team collaboration [105].

A review of the above literature, including human-agent teams, spatial awareness, team cognition, and nonverbal communication, has revealed the following research gaps that this study aims to fill. First, though much research has been conducted relating to the development of spatial awareness in CSCW, little is known regarding how this information is used comparatively by different human-only and human-agent team compositions to develop team cognition (RQ1). Notably, much of the human-agent teamwork literature focuses on differences between human-only and human-agent teams [80] with few studies that have investigated how varying the number of agents on the human-agent team might affect team processes like team cognition [68, 73]. Second, though it is known that CSCW spatial awareness tools promote team outcomes such as performance and perceived team cognition, little is known regarding how such outcomes are supported comparatively between human-only and human-agent team compositions (RQ2).

3 METHODS

The current study employs a mixed-methods design to investigate the role of spatial awareness in team cognition development in varying compositions of human-agent teams versus human-only teams, its effects on outcomes of team cognition, and its interaction with team composition. The experiment utilized the team emergency response simulation known as NeoCITIES, a platform long recognized for its efficacy in teaming research [39, 44, 46, 63]. The study manipulates spatial information of the task space into two levels (low spatial information, high spatial information) and team composition into three levels (see Table 1). All independent variables were examined, resulting in a 2x3 factorial design completed between subjects (see Table 1).

Table 1. Experimental Conditions

Condition Number	Spatial Information Condition	Team Composition Condition
Condition 1 (HSpIHHH)	High	Human-Human-Human
Condition 2 (HSpIHHA)	High	Human-Human-Agent
Condition 3 (HSpIHAA)	High	Human-Agent-Agent
Condition 4 (LSpIHHH)	Low	Human-Human-Human
Condition 5 (LSpIHHA)	Low	Human-Human-Agent
Condition 6 (LSpIHAA)	Low	Human-Agent-Agent

Note: The "HSpI" in Conditions 1-3 refers to high spatial information available in these conditions (spatially accurate map). The last three letters (e.g., HHA: Human-Human-Agent), refer to the team composition.

3.1 NeoCITIES Task and Roles

NeoCITIES is a well established platform primarily used for teaming research [43, 46, 92]. NeoCITIES uses a fictional college town (Figure 1) to simulate a team-based emergency response scenario that places three teammates into interdependent roles of Police, Fire, and Hazmat. Each role must utilize a triad of resources unique to their specific role to successfully respond to a series of emergency events over time, specifically the roles resources are (1) Police: Investigator, SWAT Van, Squad Car; (2) Fire: Investigator, Fire Truck, Ambulance; (3) Hazmat: Investigator, Bomb Squad, Chemical Truck. The interdependency between the three roles and the multitude of solutions allows for complex interactions between team members to take place and develop team cognition [39].

The selection of team size (triads) was made after careful consideration as smaller teams (dyads) are too small to participate in more complex group collaboration [2, 72, 103]. Further, human-agent teaming research often selects triads as they are the smallest team size without the limitations of dyad teaming [21, 66, 73]. Additionally, the NeoCITIES platform is currently undergoing a redesign effort to support open-source access (contact the authors for preview access).

The interface of NeoCITIES can be seen in Figure 1 and represents an emergency response management console. Each of the three-team members assumes the responsibility of supervising three resources and dispatching them to emergencies around the town in coordination with their teammates. A consistent set of tools is offered across the interface to each team member, including a list of their resources, information on active events (their required resources, description, and the distance of each required resource), all resources' current destination, and a chat feature to communicate with teammates. Additionally, those in the high spatial information had access to a spatially accurate map that displayed the town, all three players' home base, resources, and all active emergency events. The players' home base, which would be their current location at the start

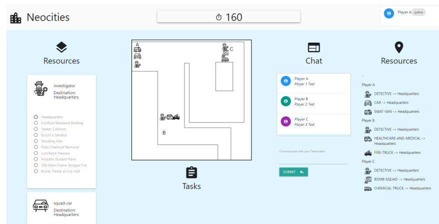


Fig. 1. NeoCITIES Home Screen Interface

of each round, is identified by their corresponding letter ID. The location of their home base never changed, and the location of all the resources they deployed to emergency events was updated and displayed to the team in real-time.

Four unique rounds of the NeoCITIES simulation were developed that each lasted nine minutes and had nine emergency events. The emergency events and their required resources (see Table 2) did not change across rounds, but the location of each resource did change across rounds. Because the first round was for training, the team-based emergency events (i.e., Tanker Collision) were placed equidistant from all team members and solo emergency events close to the required resource. Each subsequent round placed team events within an area that made them attainable while placing individual events a challenging distance away, with no changes made to the overall difficulty across rounds. This implementation meant participants either had to perform at a high level to respond to every event correctly or, if necessary, choose which event to prioritize based on its severity and benefit to team performance. Table 2 details all events and resources requirements. Additionally, some resources had different speeds, such as the Fire Truck, which was the fastest and could cover more space on the map than the slowest resources like the Ambulance and Chemical Truck. Event severity was another factor that participants considered as some events carried a higher severity level and therefore a higher score if completed successfully. The severity scale ranged from 1 to 3 (3 being high severity), based on the number of required resources and speed of those resources. With these factors to consider and held constant across all conditions, the simulation represents a sophisticated task space that requires extensive collaboration to perform at a high level.

Table 2. Sample NeoCITIES Events and Necessary Resources to Complete Them

Order	**Emergency Event**	**Resources Needed**
1.	Football Weekend Briefing	Investigator
2.	Tanker Collision	Squad Car, Fire Truck, Chemical Truck *(In That Order)*
3.	Escort a Senator	SWAT Van
4.	Smoking Kills	Fire Truck
5.	Field Chemical Removal	Chemical Truck
6.	Luncheon Nausea	Ambulance, Investigator
7.	Possible Student Rave	Investigator, Squad Car
8.	Old Main Frame Shoppe Fire	Investigator, Fire Truck
9.	City Hall Bomb Threat	Bomb Squad, Investigator

3.1.1 NeoCITIES Spatial Awareness. Essential to the validity of the current study is the effective manipulation of spatial information levels within the NeoCITIES simulation. Both the low and high spatial information conditions were provided with all the information necessary to be successful in the simulation, with the only difference between the two being the presence of a real-time spatially accurate map. However, both spatial information conditions had access to necessary information like the current destination for all nine of the teams' resources and the number of in-game minutes away each required resource was from an event.

The presence of a spatially accurate extension of the participant's representation within the task space represents spatial information in the current study [33, 41]. The level of spatial information provided to participants was manipulated by including or excluding a real-time spatially accurate map of the task space. The real-time map displayed the headquarters of all three teammates, the current location of all nine team resources, and the current location of all active events. Those without the spatial representation were in the low spatial information condition, and those with the spatial representation were in the high spatial information condition. The high spatial information condition allowed for implicit communication by enabling human teammates to observe teammate patterns and tendencies over time, indicate teammate strategies by displaying teammate resource direction towards events, and displaying past teammates' actions as resources traveled away from completed events.

3.2 AI-Agent

An expert system was programmed to take on the role of an autonomous agent in the study, capable of taking on the Fire and Hazmat roles and allocating its resources to emergencies with accuracy and flexibility to its teammates' various needs. The expert system only applied to Conditions 2, 3, 5, and 6 and took over the Fire and Hazmat role in Conditions 3 and 6 and only the Hazmat role in Conditions 2 and 5. Expert systems are an applied branch of AI capable of representing expert-level human ability [54], and the autonomous agent emulated this by constantly reassessing the current state of the game and allocating resources based on its assessment to maximize team performance. An expert system was chosen over more modern forms of AI (i.e., RL) due to the enhanced control and transparency it offered the experiment. Specifically, part of the current NeoCITIES redesign has included the design and creation of an autonomous teammate expert system. The expert system is designed to send resources by executing rules to create a "collaborative" mentality with it to the team, which it used to replicate its teammates' levels of awareness to assist them more effectively [9]. The following are a representative sample of the major rules followed by the expert system: (1) If an event appears that requires a role-exclusive resource and that resource is free, then send that resource; (2) If an event appears that requires a role-exclusive resource, but that resource is currently on the way to a different task, then wait for the resource to arrive at the original task; (3) If an event appears that requires a generic resource, and your resource is either closest or the others are occupied, then send that resource; (4) If an event's timer is approaching a time that makes it unable for your generic resource to reach it, no one else is sending a generic resource to it, and your generic resource is free, then send your generic resource to the event.

The communication of the agent teammate was limited for three critical reasons: (1) specifically investigate the potential benefits offered by access to higher levels of spatial information for human-agent teams; (2) to better reflect modern autonomous agents difficulty engaging in human communication[107]; (3) humans were allowed to communicate to better reflect existing human-agent team implementations, as limiting human communication would not generalize to real-world applications. This design best reflected current human-agent teams and allowed the study to investigate these teams' unique communication situations.

3.3 Participants

Twelve teams participated in each condition, except the LSpIHHA condition, which had 13 teams (overschedule). The HSpIHHH condition also had two teams dropped from data analysis due to technical difficulties during the session (weather-related power outage). This resulted in 141 participants taking part in the experiment (see Table 3) at an average age of 18.5 (*SD* = .76) with 52 males and 88 females. Participants were recruited from a departmental subject pool at a large university in the United States of America and were given course credit as an incentive for their participation.

Table 3. Participant Numbers

High Spatial Awareness Condition: **66** (34 Teams)		
HSpIHHH: **30** (10 Teams)	HSpIHHA: **24** (12 Teams)	HSpIHAA: **12** (12 Teams)

Low Spatial Awareness Condition: **74** (37 Teams)		
LSpIHHH: **36** (12 Teams)	LSpIHHA: **26** (13 Teams)	LSpIHAA: **12** (12 Teams)

3.4 Procedure

Due to the severe constraints imposed on in-person research by the COVID-19 global pandemic [87], the entirety of the current study was conducted remotely through Zoom meetings. The Zoom remote meeting tool has seen a significant increase in popularity since the beginning of the pandemic and is a reliable means of data collection for academic research [3, 31]. Each experiment session was administered and monitored by a trained experimenter following a protocol approved by the Institutional Review Board. Participants were instructed and monitored through audio and video channels throughout the experiment to ensure the experimental tasks were taken seriously, and any participants found to be severely distracted or unable to complete the experiment were dismissed. This monitoring involved observation and checks on the participants' attention, which resulted in a single warning if failed and dismissal for a second infraction. These checks included observing answers to survey questions (i.e., answers to reverse coded questions, time taken), ability to respond to inquiries from the experimenter, and observing their performance within the task as inattention was quickly revealed by inactivity.

The study began by collecting informed consent from each participant invited to the Zoom meeting and then collecting demographic information using an online survey. After the survey, the researchers went over the NeoCITIES task in detail, randomly assigned participants to roles, and informed them what roles would be taken by an AI-agent teammate (if applicable). At this point, the researcher verbally walked participants through a detailed training page with text information and short videos showcasing the NeoCITIES task and user interface features. This training was followed by a live training session where all the participants could ask questions about the task and interface as they completed the first round together. Once the training round was completed, the teams were told they could no longer ask questions and proceeded to complete the remaining three rounds in secession for a total time of 36 minutes, which past literature has identified as being adequate to developing team cognition [68, 73]. With the team task complete, participants then completed the task and team mental model measures, perceived team cognition measure, and qualitative free-response questions.

3.5 Measures

3.5.1 Team and Task Mental Model. Task mental models were measured using paired sentence comparisons [7], a method common to the shared mental model literature [62, 70]. Participants are asked to compare the relationship between the important attributes of the task necessary to complete it effectively. Such attributes were identified by conducting task analyses with subject matter experts of the task (three NeoCITIES simulation designers). Participants judge how positively related, unrelated, or negatively related each attribute is to the others, producing a network of commonality between the attributes revealing the structure of their task mental model. The attributes elicited from the task analysis used to measure participant's task mental models included the following: *(1) familiarization with the simulation layout, (2) determine which resources are at your individual disposal, (3) determine the location of event, (4) send resource to event if available, (5) learn what resources your teammates have, (6) recall resources, (7) determine resource allocation based on event importance, (8) send resource in the correct order for critical events.*

Measurement of participants' team mental models follows the same methodology as the task mental model except the attributes of teamwork are more generalized and are sourced from past literature [52, 62]. The attributes used to measure team mental models were: *(1) amount of information, (2) quality of information, (3) role/responsibility, (4) interaction patterns, (5) communication channels, (6) role interdependencies, (7) teammates' skill, (8) teammates' attitudes, (9) teammates' preferences.*

3.5.2 Mental Model Similarity. Mental model similarity within teams was measured using the Pathfinder network-scaling algorithm [96], which is a standard methodology in shared mental model research [62, 70, 71]. The Pathfinder program uses the matrices produced by the participants pairwise comparisons to create graphical representations of the answers as a mental model network. Each attribute represents a node in the network, and the assessed relationships between attributes represent the edges between the nodes. Pathfinder can assess two individual networks' similarity and provide a rating between 0 (indicating no similarity) and 1 (indicating perfect similarity). This similarity assessment was completed pairwise in teams of three human members (HSpIHHH, LSpIHHH) for a total of three similarity ratings, which were then averaged for the overall similarity rating, a common practice in past research [55, 90]. Teams of two humans only received one similarity rating between the two human team members, and teams with only one human received no similarity rating. The process of assessing mental model similarity was the same for both task and team mental models.

3.5.3 Perceived Team Cognition. Measures of perceived team cognition were collected using the Teamwork Schema Questionnaire [81, 84]. The survey measure asked participants to rate how important a series of statements was to their idea of teamwork. The questionnaire then asks participants to rate how important they believe the same series of statements is to their human teammates' idea of teamwork and, if applicable, how important they believe the statements are to their autonomous agent teammate's idea of teamwork. The absolute difference between participant's personal opinions of teamwork and their assessment of their teammates' definition of teamwork was evaluated, summed, and then scaled by the number of comparisons made on the team, placing scores for this measure between 0 and 84, with lower scores indicating higher perceived team cognition.

3.5.4 Team Performance.

$$EventScore = \left(\sum_{CompletedEvents} CompletedScore_{event} \right) + \left(\sum_{FailedEvents} FailedScore_{event} \right) \quad (1)$$

$$TeamScore = \left(\frac{WorstScore - EventScore}{WorstScore - BestScore} \right) * 100 \quad (2)$$

The NeoCITIES platform automatically provides numerical scores to teams after each round using equations developed in past research using NeoCITIES (see Equations 1 - 2) [68, 94]. CompletedScore denotes the time it takes for a team to complete an event, which is scaled by the event's severity as participants are told that higher severity events should be completed sooner than others. FailedScore is the total time an event took when failed plus a penalty for each wasted resource sent to an event that was not ultimately completed. EventScore (Equation 1) represents the total, time-based score a team receives for a session, which is the summation of all CompletedScores for completed events and FailedScores for failed events.

A lower EventScore would denote a better performing team from a time perspective; however, scores were normalized into a final percent-based metric to make the presentation of results more readily readable. BestScore is a total score that denotes the summation of all possible best time-based scores for each event provided to participants in a session. WorstScore is the total summation of all time-based scores when calculating the worst possible FailedScores for each event. Finally, TeamScore (Equation 2), which is the measurement reported by this article, is a percentage taken from the ratio of (a) the difference between a team's WorstScore and EventScore and (b) the difference between a team's WorstScore and their BestScore. The resulting TeamScore is a percent-based score where higher percentages equate to higher levels of team performance.

3.5.5 Qualitative Questions and Chat Frequency. A series of open-ended questions were designed to elicit the participants lived experiences specifically concerning the study's research questions. A thematic analysis was conducted to analyze all participant responses to identify major themes that relate directly to the study's research questions [8, 29, 98], with quotes identified to represent the identified themes. Additionally, data for the frequency of chats between teammates during the NeoCITIES task was captured.

Specifically, the thematic analysis involved four major phases: 1) two authors read through each of the open-ended responses to achieve an understanding of how spatial awareness and team composition affected the development of team cognition; 2) the same two authors re-reviewed the responses and identified major themes and sub-themes describing how and why spatial awareness and team composition affected team cognition development (and how the two variables interacted); 3) all authors of the study debated and reviewed the themes and sub-themes identified in the previous phase (disagreements were debated extensively until a consensus was reached); 4) one of the two authors involved in Phase 1 and 2 identified quotes that powerfully conveyed the meaning of each significant theme and sub-theme; 5) all authors again reviewed the major themes and sub-themes using the quotes identified in Phase 4 to further refine and develop them into a concise synthesis of the participants experience with the role spatial awareness and team composition had on team cognition development in human-agent teams.

4 RESULTS

The findings are presented in two parts, quantitative and qualitative, to answer our two research questions. Both sections address data answering each of the two main research questions and their subsidiaries.

4.1 Quantitative Analysis

The quantitative findings are separated into two major sections based on the dependent variable (performance, team cognition). The standard deviation and mean for each dependent variable measured can be seen in Table 4. Measures of the dependent variable performance are covered first, while the measures of team cognition conclude the section. Lastly, all statistical assumptions (i.e., homogeneity of variance and normality) for each test were met unless otherwise stated.

A two-factor (spatial information condition and team condition) repeated measures ANCOVA was used to determine whether the conditions differed in their performance while controlling for chat frequency. All post-hoc analyses for the repeated measures ANCOVA used Holm corrected p-values. For task and team mental model similarity factorial ANOVAs were used to compare the effects of spatial information (low, high) and team condition (LSpIHHH, LSpIHHA), which only included team conditions with at least two humans. Finally, factorial ANOVAs were used to compare the main effects of spatial information condition and team condition on perceived levels of team cognition. The team composition conditions also allowed for an analysis of the difference in perceived team cognition between human and agent teammates. A factorial ANOVA was conducted to determine how spatial information (high, low) and teammate type (agent, human) affect perceived team cognition. Analyses for team cognition related variables and perceived team performance used Games-Howell post-hoc tests and did not use the covariate of chat frequency as it was not found to have any significant effect on any of the dependent variables (all F statistics < .06).

Table 4. Mean and Standard Deviations for Dependent Variables

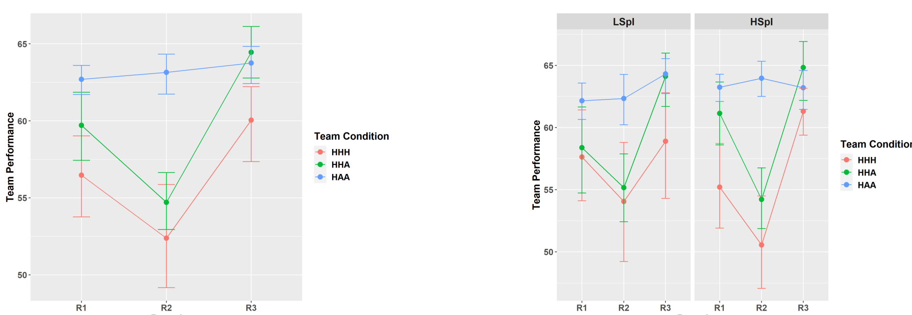
Measure	HSpIHHH Mean (N)	SD	HSpIHHA Mean (N)	SD	HSpIHAA Mean (N)	SD
Team Performance	55.69 (10)	4.34	60.06 (12)	4.47	63.47 (12)	1.14
Perceived Team Cognition	7.73 (10)	2.78	15.27 (12)	6.16	16.50 (12)	12.18
Team Mental Model Similarity	0.24 (10)	0.07	0.31 (12)	0.13	*N/A* (0)	*N/A*
Task Mental Model Similarity	0.33 (10)	0.05	0.37 (12)	0.17	*N/A* (0)	*N/A*
Measure	**LSpIHHH Mean (N)**	**SD**	**LSpIHHA Mean (N)**	**SD**	**LSpIHAA Mean (N)**	**SD**
Team Performance	56.86 (11)	5.90	59.22 (13)	4.56	62.93 (12)	1.87
Perceived Team Cognition	8.06 (12)	4.20	12.58 (13)	6.21	23.33 (12)	15.32
Team Mental Model Similarity	0.31 (12)	0.08	0.26 (13)	0.08	*N/A* (0)	*N/A*
Task Mental Model Similarity	0.32 (12)	0.08	0.33 (13)	0.14	*N/A* (0)	*N/A*

Ranges: Team Performance (0-100); Perceived Team Cognition (0-84); Team Mental Model Similarity (0-1); Task Mental Model Similarity (0-1) *Note: Lower values for perceived team cognition are better.*

4.1.1 Spatial Awareness' Effect on Team Effectiveness. The RMANCOVA revealed a significant main effect of round on team performance, $F(2, 126) = 27.77$, $p < .001$, $\eta_p^2 = .31$, such that teams performed significantly worse in Round 2 ($M = 56.90, SD = 7.06$) than both Round 1 ($M = 59.76, SD = 5.63$) and Round 3 ($M = 62.89, SD = 4.82$), while teams had the highest performance in Round 3 ($p < .001$). The main effect of spatial information level was insignificant $F(1, 63) < .01$, $p = .972$, $\eta^2 < .01$; however, the main effect of team condition was significant $F(2, 63) = 10.89$, $p < .001$, $\eta_p^2 = .26$. Specifically, HAA teams ($M = 63.20, SD = 2.90$) performed significantly better than both HHA ($M = 59.62, SD = 6.40$) and HHH teams ($M = 56.30, SD = 7.23$), while HHA teams also significantly outperformed HHH teams.

The interaction between round and spatial information level was not significant $F(2, 126) = .99$, $p = .374$, $\eta_p^2 = .02$. Alternatively, the interaction between round and team condition was significant $F(4, 126) = 8.20$, $p < .001$, $\eta_p^2 = .21$; see Figure 2a. The interaction was characterized by HHA teams ($M = 64.46, SD = 4.27$) eventually outperforming HHH teams ($M = 60.04, SD = 6.01$) in Round 3.

Additionally, the interaction between round, spatial information level, and team condition was significant $F(4, 126) = 2.51$, $p < .05$, $\eta_p^2 = .07$. Follow-up analyses of the simple main effects of each variable indicated: (1) no significant simple main effects of spatial information level; (2) significant simple main effects of Round on LSpIHHA, HSpIHHH, and HSpIHHA teams; (3) significant simple main effects of team condition on LSpI teams during Round 2 and HSpI teams during Rounds 1 and 2. This interaction is best conveyed in Figure 2b, as the simple effects of both Round and team condition are visually displayed. Specifically for round, LSpIHHA teams performance significantly improved in Round 3 ($M = 64.12, SD = 4.40$) compared to Rounds 1 and 2. HSpIHHA team performance dropped significantly from Round 1 ($M = 61.14, SD = 4.65$) to Round 2 ($M = 54.22, SD = 4.55$) and then peaked in Round 3 ($M = 64.83, SD = 4.29$), while HSpIHHH teams performance rose significantly in Round 3 ($M = 61.30, SD = 3.27$) compared to the previous rounds. Furthermore, for team condition, LSpIHAA teams ($M = 62.33, SD = 3.80$) outperformed LSpIHHA ($M = 55.16, SD = 5.36$) and LSpIHAA ($M = 54.05, SD = 8.10$) teams in Round 1. For the high spatial information condition the HSpIHAA teams ($M = 63.24, SD = 2.09$) outperformed HSpIHHH teams ($M = 55.21, SD = 5.99$) in Round 1, but HSpIHAA teams ($M = 63.96, SD = 2.70$) in Round 2 outperformed both the HSpIHHH ($M = 50.55, SD = 6.65$) and HSpIHHA teams ($M = 54.22, SD = 4.55$). Lastly, the interaction between spatial information and team condition was insignificant $F(2, 63) = .44$, $p = .647$, $\eta_p^2 = .01$.



(a) (b)

Fig. 2. Graphs displaying the per round measures of objective team score. Results split based on team composition condition (2a) and further split based on the spatial information condition (2b). Error bars represent bootstrapped 95% confidence intervals.

4.1.1.1 Summary. Highlighting the main effects addressing RQ2 and RQ2.1, teams did respond to each round differently, with performance being the highest in Round 3, followed by Round 1 and 2. The main effect of round shows that teams' performance did improve over time. There was no main effect of spatial information, which highlights that averaged across all three team conditions, the teams were not hindered or advantaged by the presence or lack of more spatial information. However, team performance was affected by team condition, as both team conditions with agent teammates outperformed the human-only condition, and teams with two agents outperformed those with a single agent. This effect is not surprising given the fact that an expert system powered the agent teammates. Furthermore, the chat frequency metric was found to be a significant covariate ($F = 5.34$, $p < .01$, $\eta_p^2 = .08$), though parameter estimates did not have sufficient power to determine the direction of the effect. Finally, the takeaway for the three-way interaction can be simplified down to the difference in the performance levels of the HSpI teams compared to their LSpI across the rounds. Unfortunately, there was insufficient power to discern the specific differences through simple main effects of spatial information on team performance.

4.1.2 *Spatial Awareness' Effect on Team Cognition.*

4.1.2.1 Spatial information's effect on task mental model similarity. A main effect of spatial information was insignificant ($F(1, 43) = .52$, $p = .473$, $\eta_p^2 = .01$; see Figure 3a). Additionally, a main effect of team condition ($F(1, 43) = .43$, $p = .516$, $\eta_p^2 < .01$) and interaction between spatial information and team condition were insignificant ($F(1, 43) = .13$, $p = .721$, $\eta_p^2 < .01$).

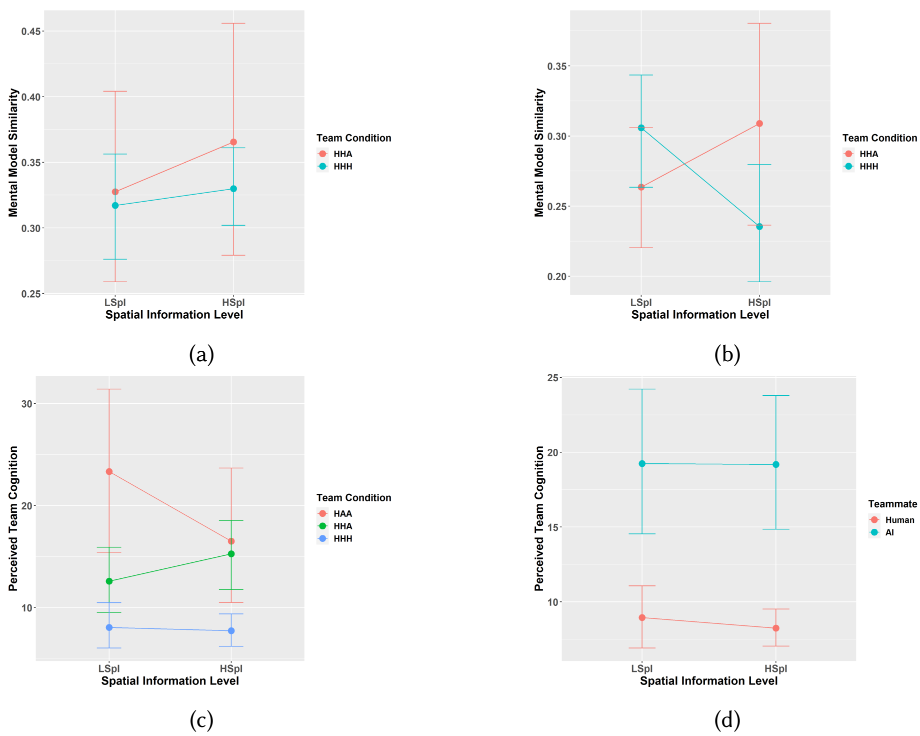


Fig. 3. Spatial information's effect on team mental model similarity (3a and 3b) and perceived team cognition (3c and 3d. Graphs also display differences between team composition condition (3a, 3b, and 3c) and perceptions for human teammates versus AI-agent teammates (3d). Error bars represent bootstrapped 95% confidence intervals.

4.1.2.2 Spatial information's effect on team mental model similarity. The analysis found the main effect of spatial information and team condition to be insignificant, $F(1, 43) = .20$, $p = .654$, $\eta_p^2 < .01$ and $F(1, 43) = .31$, $p = .578$, $\eta_p^2 < .01$, respectively. However, the interaction effect between spatial information and team composition was significant, $F(1, 43) = 4.36$, $p < .05$, $\eta_p^2 = .09$. The interaction effect was ordinal as seen in Figure 3b.

The analysis of the interaction's simple main effects for team condition and spatial information only neared significance ($p = .07$ and .08 respectively). The HSpIHHA teams trended towards having higher team mental model similarity ($M = .31$, $SE = .03$) than LSpIHHA teams ($M = .26$, $SE = .03$), while HSpIHHH ($M = .24$, $SE = .03$) and LSpIHHH ($M = .31$, $SE = .03$) teams experienced the opposite trend.

4.1.2.3 Spatial information's effect on perceived team cognition. The main effect of spatial information was insignificant, $F(1, 65) = .47$, $p = .494$, $\eta_p^2 = .01$; however the main effect of team condition was significant, $F(2, 65) = 10.03$, $p < .001$, $\eta_p^2 = .24$; see Figure 3c. The main effect of team condition was such that HHH teams ($M = 7.91, SD = 3.54$) had significantly better perceived team cognition than either the HHA ($M = 13.87, SD = 6.21$) or HAA teams ($M = 19.92, SD = 13.97$). Lastly, the interaction effect of spatial information and team composition was not significant $F(2, 65) = 1.75$, $p = .182$, $\eta_p^2 = .05$.

Analyzing the difference in perceived team cognition with human teammates versus agent teammates revealed that spatial information did not have a significant main effect on perceived team cognition $F(1, 90) = .08$, $p = .78$, $\eta_p^2 < .01$; however, the main effect of teammate type was significant $F(1, 90) = 25.79$, $p < .001$, $\eta_p^2 = .22$. Specifically, teams' perceived more team cognition with their human teammate ($M = 8.62$, $SD = 4.58$) than their agent teammate ($M = 19.21$, $SD = 11.87$). Lastly, the interaction effect between spatial information and team composition was not significant, $F(1, 90) = .05$, $p = .820$, $\eta_p^2 < .01$ (see Figure 3d).

4.1.2.4 Summary. Addressing RQ1 and RQ1.1, the interaction effect between team condition and spatial information had inconclusive post-hoc analyses; however, the trend of the data was such that HSpIHHA teams trended towards having more team mental model similarity than LSpIHHA teams, while the reverse was true for HHH teams (LSpIHHH > HSpIHHH). Interestingly, the same was not valid for task mental model similarity, suggesting that spatial information benefits the development of team norms, coordination, and communication strategies more than task knowledge. Looking to RQ2 and RQ2.1, perceptions of team cognition were higher for human-only teams compared to human-agent teams regardless of spatial information level, which aligns with the sentiment of past research [100, 108]. This finding was also true when comparing how much perceived team cognition participants had with their human teammate versus their agent teammate.

4.2 Examining the Interplay of Spatial Awareness and Team Cognition in Human-Agent Teams

The following qualitative themes provide essential context to the quantitative data reported previously, detailing participants' objective experiences of how spatial information and team composition did, or did not, affect their team's development of team cognition. A unique identifier and condition code identify participant quotes (see Table 1). If necessary, additional context is inserted into participants' quotes from the question they were answering at the time, indicated using square brackets ([example]).

4.2.1 High Spatial Information Jump-Starts the Development of Team Cognition. The first major theme of the qualitative results pointedly addresses RQ1 and RQ1.1, detailing how spatial awareness impacts the development of team cognition and its outcomes in human-only teams versus human-agent teams of varying composition. The sub-themes highlight how spatial information acts as an accelerant of team cognition development, how its absence may lead to inaccurate mental models, and how it is still not a complete substitute for explicit agent communication.

A clear theme for the role of spatial information was its ability to rapidly develop team members' mental models of the simulation space. This acceleration was evident as many participants without a spatial representation of the task space noted their inability to conceptualize a mental model of the space, locations, resources, and teammates':

> *"I feel like it was more difficult not having a map. My spatial awareness was challenged. I needed to put most my focus on how long it would take for my resource to arrive instead of using a visual aid." (P429-LSpIHHH)*
> *"I believe it [not having a spatial map] hindered it [team cognition] because we couldn't visually see where everything was." (P500-LSpIHHA)*

"[Not having a spatial map] Hurt [team cognition]. [It was] Harder to form a mental map of the game map." (P511-LSpIHHA)

Participants working in the condition without a spatial map repeatedly noted how lacking one negatively affected their ability to initially develop a mental model of the simulation. For example, P511 identifies the lack of a spatial map as the driving factor in their team's inability to form a collective mental map of the simulation space. Additionally, P429 specifically states how not having a spatial map reduced their cognitive resources during decision points. Further still, the lack of a spatial map can lead to inaccuracies between teammates in this condition, as shown in the following sub-theme.

4.2.1.1 The lack of high spatial information levels can foster inaccurate and varied mental models. Many participants reported trying to visualize the simulation's task space and form a mental model of it, even with the lack of a concrete representation of that space to use for reference:

"I feel that not having the spatial map hindered my team [cognition] because, for me, I am a visual person so it would've been better to see where everyone's resources are rather than trying to figure out the time it would take." (P426-LSpIHHH)
"I think it [not having a spatial map] hindered it [team cognition] because I would have liked to have seen a map at the beginning of the task but eventually I got the hang of it. We managed to see where we needed to be." (P431-LSpIHHH))

The lack of a ground truth reference point while building a mental model of the task space can lead to inaccuracies between teammates. P431's quote mentions expending cognitive resources during decision points, indicating that while they were eventually able to form a mental model of the simulation, it took time and effort to do so. The quotes from P426 and P431 also show that human teammates will attempt to form a mental model of the simulation and use that mental model whether it is accurate or not. These mental models are likely to suffer from a great deal of variability, subsequently reducing effective team cognition. This assertion is supported by this study's quantitative data in team mental model similarity and appears especially important for human-agent teams.

Spatial information also excelled at abstracting away complex information for executing on mental models, allowing information to be conveyed to the participants using only a glance, which several participants reported was a distinct advantage when reaching a decision point:

"[The spatial map] Helped because I could visualize where everyone was and where they were going." (P300-HSpIHAA)
"It helped our team cognition because then we could visualize the meaning of how many minutes away we were." (P111-HSpIHHH)
"[The spatial map] Allowed for (sic) me to comprehend visually where they were going." (P306-HSpIHAA)

The quality of spatial information was especially prevalent to the teams with agent teammates, potentially indicating that they valued the ability to rapidly assess the current state of the simulation more than the human-only teams, aligning with the quantitative results. P306 and P300's quotes both reflect this assumption, but the advantage was not limited to human-agent teams as P111 conveys their appreciation for the spatial map's ability to quickly abstract away time and distance for effective decision making as well. However, a few of the above quotes demonstrate (particularly P111 and P426) human-only teams are not entirely unaided by the inclusion of spatial information despite the quantitative results demonstrating a lower benefit to their team cognition. P426's quote may help explain this as it evidences the influence of individual differences (i.e., being a "visual learner"). Thus, individuals in human-only teams may not be entirely exempt from the benefits of spatial information, but rather, its effects are much more potent at a team level for human-agent teams based on the results of this study. Such quotes and P111's lend credence to the assertion that the utility of spatial information in human-only teams was especially subject to individual differences.

4.2.1.2 High spatial information ***alone*** *still isn't a complete substitute for explicit agent communication.* A key difference between the human-only and human-agent teams was the ability to communicate explicitly using text chat. While participants could make requests of the agent, it could not respond or give status updates, which must be kept in mind when interpreting these results. As such, the following theme highlights that many participants did not feel that spatial information alone was enough to compensate for direct, explicit communication, despite spatial information's ability to afford teams with more chances for implicit information and communication. Many participants were able to take advantage of this implicit communication to recognize patterns in teammate behavior, as the following participant quotes indicate:

> *"I think it allowed us to know where everyone was and where they were headed so that we could plan our strategy better." (P203-HSpIHHA)*
> *"We did a great job at adapting to each others movements." (P222-HSpIHHA))*

Alternatively, many participants with access to high spatial information conveyed dissatisfaction with their agent teammate because of its lack of direct communication. It appears that human teammates do not believe implicit communication is effective enough to develop team cognition with their agent teammate:

> *"[Interacting with the agent was] Alright, I did not like that we could not communicate with it though." (P202-HSpIHHA)*
> *"Interaction [with the agent] was difficult since it could only be done through seeing where each resource was going." (P309-HSpIHAA)*

P202 and P309 noted specific desires to explicitly communicate with the agent teammate, and P309 states that implicit communication was not enough. These comments highlight that simple spatial information may not be enough to overcome the lack of effective agent communication and that the ability to communicate with the agents through the spatial medium may be a favorable middle ground.

Additionally, it became clear that while spatial information is a vital tool for teams, too much of it can become detrimental to teams and their effectiveness. Several participants in the high spatial information condition reported that it became distracting or unnecessary throughout their task work:

> *"In reality the map was not needed. While I didn't allow it to be a distraction for myself I could see how it could cause inefficiency in a group." (P115-HSpIHHH)*
> *"The spatial map did not help since the distance of the resources was listed in the specific task and in a way it was more distracting than anything else." (P109-HSpIHHH) "It [spatial map] neither helped or hindered [team cognition], we focused on the tasks at the bottom and where each person [agent] was sending their dispatches on the right hand side." (P308-HSpIHAA)*

P115 notes that effective performance was still possible without the map and only felt it served as a distraction, and P308 reiterates this sentiment. Its degree of usefulness to anyone was likely dependent upon various individual differences; however, we know that human-agent teams did not suffer any significant decrease in performance despite this and instead saw increases to team cognition. Based on chat frequency, human-only teams likely saw explicit communication as a more direct means of coordination and thus did not benefit from the spatial information to the same degree as human-agent teams did.

4.2.2 Human-Agent Teams Benefit from High Spatial Awareness to Develop Team Cognition Iteratively. The final major theme also addresses RQ2 and RQ2.1, specifically highlighting how human-agent teams in particular benefit from spatial information and how it affects the outcomes of team cognition. The human-agent teams benefited greatly from their ability to develop team cognition iteratively through their enhanced need to verify agent actions and build confidence, and their relation of the spatial information to explainable AI-agents and enhanced decision making.

Participants in human-agent teams expressed a consistent theme of appreciating high spatial information because it allowed them to continuously check in on the agent's actions. This theme was also echoed in the previous section and related to spatial information's ability to convey complex information quickly:

> *"Yes, [the spatial map was useful] because you can see what they [the agent] are doing." (P201-HSpIHHA)*
> *"I was always checking to see if it [the agent] was doing the correct task." (P517-LSpIHHA)*
> *"[The spatial map] Helped, the map showed that the other teammate [agent] was doing all they could to complete the tasks." (P211-HSpIHHA)*

Participants do not appear to have the same level of confidence or familiarity in their agent teammate as their human teammate, partially reflected in the quantitative data regarding perceived team cognition. While it is not ideal that these teams appear to start on the wrong foot with lower confidence levels in one of their teammates, participants' responses indicate that their spatial awareness allows them to build confidence in their teammate over time. For example, P211 stated how much high spatial information helped them understand that the agent teammate was doing all it could to help them, building confidence over time.

Additionally, the participants noted how important their verification of the agent's actions was during critical decision points with overlapping responsibilities:

> *"I think we did [use the spatial map to monitor the agent], we had to be aware of it [the agent] so that we weren't double dipping on the tasks." (P203-HSpIHHA)*
> *"I just had to watch my units but check where they sent their investigators." (P607-LSpIHAA)*

P203 conveys how often they used spatial information to make effective strategic decisions in periods of overlapping responsibility, which is when team cognition becomes especially important. P607 also remarked how often they had to use the status bar (they did not have access to the map) to ensure multiple investigators were not sent to the same event, indicating they too would have benefited from high spatial information for decision making on shared responsibilities.

4.2.3.1 Humans relate spatial information to explainable AI-agents. Spatial information also contributes to creating explainable AI-agents, as several participants connected high spatial information to their understanding of the agent as a teammate:

> *"It [spatial map] increased the trust [in the agent] because I knew what it [the agent] was doing." (P203-HSpIHHA)*
> *"Yes [the spatial map helped]. I could monitor what the autonomous teammate was doing and therefore I realized I could trust it more." (P214-HSpIHHA)*

High spatial information was strongly associated with explainable AI-agents in the qualitative data, which is a significant finding given the importance of developing better explainable AI-agents to CSCW. P214 makes this connection incredibly clear as they reiterate a moment of realization that they could trust their agent teammate because they understood its actions due to the high spatial information.

Additionally, those participants in the low spatial information condition specifically commented on how they wished they had a spatial map to help them understand their agent teammate:

> *"Yes [a spatial map would have helped] because [without it] I could not visually see the decisions of the autonomous teammate." (P520-LSpIHHA)*
> *"Yes [a spatial map would have helped] because we could not fully monitor what they [the agent] were doing." (P515-LSpIHHA)*

Participants' ability to relate spatial information to explainable AI-agents, as these juxtaposed series of quotes indicate, is a significant finding in the progressive development of more explainable AI-agents. P520's experience is a significant example of this as they convey what is essentially the opposite experience of P214 in the previous series of quotes: they were unable to build trust and team cognition with the agent rapidly.

5 DISCUSSION

The current study addresses a series of research questions on the role of spatial information in developing team cognition in human-agent teams by manipulating team composition and the level of spatial information. Specifically, RQ1 was addressed by finding that humans leverage spatial information to jump-start their team cognition. This finding was reflected in quantitative and qualitative data, where a significant interaction with inconclusive simple main effects suggested the trend that human-agent teams with high spatial information developed higher levels of team mental model similarity than those with low spatial information. At the same time, the trend was reversed for human-only teams. Qualitative data continued to address RQ1 through RQ1.1, showing that teams with high spatial information could develop effective team cognition faster through more accurate mental models of the task space and built upon that team cognition iteratively over time with more explainable AI-agents, which was more critical to HAA teams. Concerning RQ2, there was no significant quantitative effect of spatial information on team performance. Additionally, there was no effect of spatial information on perceived team cognition. However, it was found that human-only teams *perceived* more team cognition overall and that teams perceived more team cognition with human teammates than agent teammates. The qualitative data helps answer RQ2.1 by finding that high spatial information was most helpful during critical decision points, providing a medium for explainable AI agents that participants could use to verify agent actions and allow complex information to be abstracted away into an easily perceived format. The following discussion highlights how these findings advance the existing CSCW theory and research on human-agent teams, spatial awareness, and team cognition while also providing a series of design recommendations supported by the current findings.

5.1 Spatial Information Enhances Explainable AI-agents and Accurate Team Mental Models

The introduction highlighted that properly developing effective spatial awareness is essential to human-agent teams, given the limitations of communication and perception faced by human-agent teams. Specifically, the limitations to explicit communication in the form of natural language processing [48, 91, 107], perceptual biases against agent teammates [100, 108], and generally ineffective communication within such teams [48, 91] make developing team cognition difficult. As such, the current study's findings represent a significant contribution to establishing alternative methods of communication and awareness that facilitate the development of team cognition. Specifically, human-agent teams produced higher team mental model similarity levels when given a real-time spatial representation of the simulation in their interface. This finding is the first time this effect has been noted in human-agent teams and aligns with past research on distributed human-only teams [37]. The qualitative findings also showcased that high spatial information allows the individual teammates to develop more accurate mental models less variable between teammates. This finding provides additional validation to previous qualitative human-agent teaming research concluding that implicit communication *is* used to build team cognition in human-agent teams [73]. However, the type of task and the nature of the team should be considered when interpreting these results. Specifically, spatial information traditionally only has these benefits when applied to tasks with spatial relevance (i.e., search, escape) [24, 38], so the same is likely valid for human-agent teams. Increasing team size also increases collaboration [60], which may increase the importance of spatial information.

5.2 Spatial Information Should Be Targeted Toward Critical Periods in Teaming

Spatial information is known to increase team performance in tasks where it is relevant [24, 38]. Interestingly, there was no significant effect of spatial information level on team performance in the current study, only a significant effect of team condition, though this is likely due to the use of expert systems for the agent teammates. However, human-only teams did appear to be negatively affected by high spatial information in their team mental model similarity compared to human-agent teams. This benefit to human-agent teams is likely explained through the qualitative data, which saw that they were better able to create mental models of the task space, their teammates' movements and patterns, and the ability to check up on their teammates' actions. These same benefits were likely not seen in human-only teams as explicit communication was possible for every teammate, and the benefit of high spatial information presented an overload of information that was exacerbated by a higher degree of individual differences among teammates. These factors would have caused HSpIHHH teams to struggle to develop similar team mental models. However, it is possible that given more time, HSpIHHH teams may have adapted to the amount of team information available and overcome the initial negative effect, but more research is necessary.

Regardless, such findings are necessary to enhance the effectiveness of spatial information design in human-agent teams and contribute to improved team outcomes. The qualitative data provide these valuable insights by contextualizing the quantitative results, highlighting that spatial information is essential to jump-starting effective team cognition by helping team members develop mental models of the simulation rapidly. Additionally, high levels of spatial information were beneficial to team members seeking to quickly absorb complex abstract information like distance, time to arrival, and intention [36, 37]. Participants also reported that spatial information could be distracting between critical decision points but invaluable when those critical decision points arose.

Specifically, each of those complex components of awareness could be abstracted away into a spatial-visual representation of the simulation that teammates quickly glanced at to make decisions during critical team action periods [28]. Because spatial information is crucial to effective rapid decision making, spatial components must be carefully designed for interfaces to focus on abstracting away complex information for teammates, supporting decision points, and maintaining accurate representations of the task space to help support accurate shared mental models.

5.3 Design Recommendations for Spatial Information to Improve Team Cognition in Human-Agent Teams

The following design recommendations will improve team cognition in human-agent teams alongside related outcomes like perceptions and performance. Such design recommendations are timely and exceedingly relevant given the importance of spatial information to team cognition [37], the rise of human-agent teams [80], and the difficulty such teams face in communication, and therefore team cognition development [15, 107].

5.3.1 Spatial Information Should Delineate Human Teammates from Agent Teammates to Facilitate Rapid Verification. A significant theme from the qualitative data was the value human teammates placed on spatial information for verifying agent action and commitment. This emphasis on checking up on the agent teammate(s) could be due to several factors like individual differences and or agent design; however, it is clear from this study's results that human teammates feel the need to check in on their agent teammates more often than their human teammates (a theme identified in other research as well [20, 108]). Fortunately, this desire to check in on agent teammates can be leveraged to create valuable interface features that allow human-agent collaboration through spatial information. For instance, interface features, such as path modeling, live resource tracking, and visual timers associated with resources may be more effective when used exclusively for agents in human-agent teams. This feature would provide a visual landmark to create a shared understanding and awareness by helping to differentiate agent teammates and human teammates through spatial information alone. This careful design would allow the rapid identification of teammate types in the various theatres of work that human-agent teams can inhabit [93, 104]. For instance, resource paths or resource timers shown on maps should have easily identifiable AI-agent icons above them, which would then allow humans to more rapidly identify and understand the progress of both those resources and agent teammates. By designing the spatial information component to identify agent teammates from human teammates quickly, spatial information is enhanced by lowering the cognitive resources necessary to check in on an agent teammate.

5.3.2 Spatial Information Should Only be Presented At Critical Points of Team Cognition Formation and Execution. Despite the data showcasing the positive effects of high spatial information to team cognition, it was clear that the spatial representation of the simulation was detrimental to some participants' taskwork. In order to ensure that spatial information contributes to spatial awareness when it is most effective and does not present a cognitive burden when it is not needed, an adaptive interface should be implemented. This adaptive interface would deploy itself when needed, during periods where spatial information is most important to executing on the team's shared mental model and developing them early in the task and during team decision points. These two suggested critical periods for team cognition are supported by the current study's qualitative data and should, at a minimum, be supported by an optional map (if an adaptive interface is not feasible). With an adaptive interface that offers spatial information when needed most, the user can develop an accurate mental model that is much more likely to align with their teammates. Additionally, users would be able to make quick, effective decisions and check in on their agent teammate(s) to iteratively build trust and confidence that helps support effective team cognition. These benefits would exist without the additional complexity that spatial information naturally brings to interface design, reducing the cognitive load for potential system users.

5.3.3 Spatial Information Components Should Include Interaction Elements for Decision Making and Communication. Spatial information components should offer users the ability to execute their decisions using that spatial medium. This recommendation is especially relevant given how heavily participants of the current study related high spatial information to effective decision making. Specifically, spatial information components should be designed to support the implementation of the decisions made within the task, and ideally, that action would be accomplished naturally, using the representative metaphor of the individual task.

Interfaces should be developed to support spatial information of the task space, and users should be empowered to manipulate the individual objects and goals represented and have those changes be reflected in the actual task itself. Spatial components designed in this manner allow users to connect their spatial information more deeply to their decision-making and mental model of the task and their team. Additionally, the spatial component of human-agent interfaces should also leverage this design recommendation to enable hybrid communication with the agent teammate. Human teammates may make rapid requests and responses by manipulating their symbol or resources on the spatial component. This request can bring a particular goal or event to the agent's attention, allowing for a hybrid communication that utilizes implicit and non-verbal communication between the agent and the human teammates.

5.4 Future Research and Limitations

There are a few limitations to consider when interpreting this study's findings. First is the limited qualitative responses of the LSpAHAA and HSpAHAA participant conditions, meaning there is likely missed qualitative differences between the human-agent teams. The inability to measure shared mental models in teams with only one human participant is another limitation of the current study and measurement method. The current methodology also limited agent communication, creating an imbalance in communication ability between teams. Though this design was necessary to investigate the benefits of high spatial information and was controlled for in the quantitative analysis, it remains a limitation that should be kept in mind when interpreting and or applying the results of this study. The design of the NeoCITIES interface may also represent a limitation that affected the dependent variables, but as it was applied equally across conditions, it is unlikely to have affected the analyses.

Future CSCW research should investigate how larger human-agent teams develop shared mental models in light of spatial information levels as the increase in teammates and assets would likely increase the importance of adequately developing effective spatial awareness. The current study limited the scope of human-agent teams to three members to establish a starting point for this line of inquiry, so the current findings may not generalize perfectly to larger team sizes. Additionally, future research should investigate how critical spatial awareness is to teams performing tasks of various type and complexity. As the current study is limited to the NeoCITIES context, team members in other contexts with more/less complexity will likely require more/less spatial information. This limitation on task context also motivates future research to develop openly accessible synthetic task environments to support better reproducibility of results in human-agent teaming.

6 CONCLUSION

The current study advances the CSCW literature on human-agent teams by highlighting the effects of spatial information level on team cognition development in various compositions of human-agent teams compared to human-only teams. We found that spatial awareness may enhance human-agent team cognition by jump-starting the development of team cognition in human-agent teams and provided a reference for teammates to develop accurate mental models. Additionally, spatial information was crucial during critical decision points, quickly abstracting away complex information and providing a quick way to check in on the agent teammate to help build confidence. These findings advance the CSCW literature by: 1) characterizing the effect of spatial information on human-agent team cognition development; 2) highlighting how team composition interacts with spatial information to produce different effects on team cognition; and 3) providing design recommendations for human-agent team interfaces that leverage the advantages offered by spatial awareness to enhance team cognition.

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