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Unveiling Role Dynamics in AR-Based Collaborative Inquiry

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Abstract: Augmented Reality (AR) has emerged as a transformative tool in education, offering authentic and interactive environments for collaborative inquiry. However, collaborative interaction among group members in AR-based inquiry, particularly how roles are enacted and exchanged, remains underexplored. This study investigates role interaction patterns in AR-supported collaborative inquiry and analyzes how role dynamics between group members influence learning outcomes. Eighty students working in pairs engaged in AR-based scientific inquiry tasks. Video recordings were coded and analyzed. Cluster analysis shows that three distinct patterns emerged: Balanced, Dominant, and Passive. The Balanced pattern featured reciprocal *Question–Respond–Experiment–Share* behavioral sequences; Dominant dyads exhibited leader–follower dynamics, while Passive dyads demonstrated minimal engagement and weak regulation. Quantitative results showed that active participation, regardless of balance or dominance, was associated with higher learning outcomes. These findings advance understanding of how role dynamics unfold in immersive learning environments, offering insights for promoting effective collaboration.

Introduction and related work

Augmented Reality (AR) has emerged as a promising tool for collaborative inquiry learning by embedding scientific exploration in interactive and embodied environments (Connor et al., 2024; Dunleavy et al., 2009; Li et al., 2025; Mansour et al., 2024). Prior studies have integrated AR into scientific inquiry-based learning, demonstrating that AR supports students' conceptual understanding, motivation, and engagement by allowing them to visualize and manipulate abstract phenomena (Silva et al., 2023; Upadhyay et al., 2024; Zhang et al., 2025). However, while prior studies have primarily focused on learning outcomes, limited research has explored how collaborative inquiry processes unfold in AR settings (Anna & Spyros, 2025; Buchner & Kerres, 2023). Although recent research has explored overall collaboration process in AR-supported inquiry, for example, revealing distinct modes of coordination and participation (Connor et al., 2024) or how AR affects collaboration learning (Radu & Schneider, 2022), less attention has been paid to the micro-level interaction processes within groups, particularly how roles emerge, are exchanged, and interact with one another during AR inquiry, and how these dynamics relate to learning outcomes.

The emergence and transformation of roles are critical because they reflect students' participation structures and shape the flow of collaboration (Barron, 2003; Dowell et al., 2020; Jiao et al., 2022). While role formation and transitions have been extensively examined in face-to-face and computer-supported collaborative learning (CSCL) contexts (Fischer et al., 2013; Saqr et al., 2024; Srba & Bielikova, 2014), AR introduces unique coordination challenges, such as sharing devices, manipulating digital objects, and managing visual attention between physical and virtual spaces, which can significantly affect role distribution and participation balance (Radu & Schneider, 2022). These multimodal demands may increase cognitive load and reshape how roles emerge, are exchanged, and interact during inquiry. Understanding these role dynamics is essential for designing adaptive AR learning environments that foster productive collaboration.

To address these gaps, this study aims to understand how role dynamics unfold in AR learning environments. Specifically, the research questions are as follows: (1) RQ1: What types of role interaction patterns emerge among students during AR-based collaborative inquiry, and what characterizes each? (2) RQ2: How are these role interaction patterns related to students' learning outcomes? By identifying how different role interaction patterns emerge and how they relate to learning outcomes, educators and designers can develop scaffolds that promote balanced participation and deeper inquiry learning.

Methods

Participants and AR collaborative learning environment

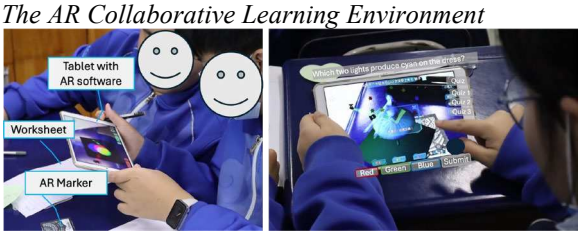
This study involved 80 seventh-grade students (37 boys, 43 girls) from two middle school classes. The intervention lasted two weeks. In the first week, students completed a 15-minute pretest designed to assess their prior knowledge of scientific concepts related to light. Subsequently, an instructor delivered a brief introduction to AR technology. During the second week, students worked in pairs (40 dyads) to complete AR inquiry tasks

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using a tablet. The inquiry topic is the mixing rules of primary colors in physics. After the session, students completed a post-test. This study developed an AR application, The Light and Color, to support interactive collaborative learning of the principles of the three primary colors of light (see Figure 1). The AR application created experimental scenarios in which students could explore light color mixing by manipulating both on-screen controls and physical markers. Students then worked in pairs to conduct the AR-based experiments collaboratively and record their scientific observations in a worksheet.

Figure 1

The AR Collaborative Learning Environment



Data collection and analysis

For RQ1, the collaborative processes of 40 groups were captured using video recordings. A rating scheme was constructed based on Storch's (2002) dyadic interaction model, which centers on the two dimensions of equality and mutuality. Equality refers to the balance of participation between partners and was further operationalized through indicators such as role distribution, role switching, and contribution balance. Mutuality reflects the degree of connectedness and responsiveness in partners' contributions and was operationalized through indicators including reciprocity, group coordination, and group cohesion. All indicators were rated on a 5-point Likert scale. To establish reliability, two researchers independently coded 30% of the videos, achieving strong agreement (Cohen's $\kappa = 0.72$). After that, one researcher coded the remaining data. Subsequently, K-means clustering was applied to the equality–mutuality ratings to identify distinct role interaction patterns. To further explore the characteristics of each pattern, four representative dyads from each cluster were selected for in-depth qualitative analysis, focusing on role distribution, role exchange, and interaction frequency features. To gain a deeper understanding of the interactive behaviors within each dyad, group interactions were coded by two researchers using the Collaborative Inquiry Interaction Behavior Coding Scheme, which included the following categories: *Question, Respond, Share, Experiment, Analyze, Negotiate, Consensus, Organization*, and *Off-task*, adapted from Hou & Wu (2011)'s social interaction framework. Inter-rater reliability was high (Cohen's $\kappa = 0.77$). Any discrepancies were examined collaboratively and resolved through consensus. During coding, the two roles in each dyad were differentiated using role-specific labels (e.g., A_Ques, B_Resp), where A and B represent each participant. Next, Sequential Pattern Mining was conducted to examine the sequential transitions of behaviors between members. A Contiguous N-gram Mining approach was used to identify frequent behavioral sequences, with the N-gram length set between 2 and 5 to capture both short and extended interaction cycles.

For RQ2, students' collaborative inquiry outcomes were assessed using scientific knowledge tests, including pre-test and post-test. Each assessment was scored out of 100 points. Scoring reliability was ensured by two researchers, with a Kappa coefficient of 0.95. ANOVA test was used to compare intergroup differences in knowledge test scores across the identified patterns.

Results

Role Interaction patterns in AR collaborative inquiry

To address RQ1, we applied K-means clustering to categorize the role interaction characteristics of 40 groups. The elbow method was used to determine the optimal number of clusters, and the solution with $K = 3$ provided the best explanatory power. Cluster 1 ($n = 14$) was characterized by high scores on both equality and mutuality, indicating balanced participation and reciprocal interaction between partners. This cluster was therefore labeled the Balanced pattern. Cluster 2 ($n = 14$) showed moderate equality and mutuality. With limited role switching and uneven contribution balance, this cluster reflected a leader-driven interaction structure and was labeled the Dominant pattern. Cluster 3 ($n = 12$) scored low on both equality and mutuality, suggesting limited participation and weak collaboration among members, and was labeled the Passive pattern.

To further examine the specific characteristics of these role interaction patterns, four representative groups from each cluster were selected for further analysis. The types of roles enacted during collaboration were first identified, followed by an examination of role distribution and exchange features across clusters. Additionally,

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we analyzed the sequential dynamics of role exchange for one representative group from each cluster, as shown in Figure 2. Finally, the interaction frequencies between roles within each dyad were recorded (See Table 1).

Table 1

Role Distribution and Interaction of Three Types

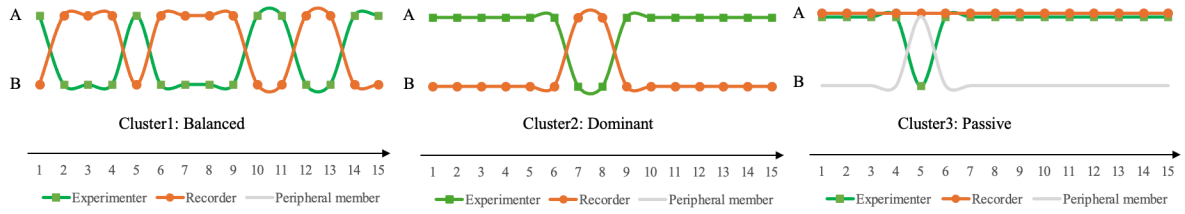
Patterns	Group No.	Role distribution		Role exchange	Role interaction Frequency (f)	
		Member A	Member B	Frequency	A → B	B → A
Balanced	9	Experimenter+ recorder	Experimenter+recorder	6	29	30
	13	Experimenter+ recorder	Experimenter+recorder	5	22	18
Dominant	1	Leader+ Experimenter	Recorder	2	25	15
	8	Experimenter	Recorder + Observer	1	18	11
	6	Recorder	Experimenter	1	12	20
Passive	12	Peripheral Member	Experimenter+Observer	1	5	16
	4	Experimenter	Peripheral Member	2	14	7

Note: Not a full list of all groups

Based on Table 1 and Figure 2, we can find that (1) Balanced Pattern. Dyads in this cluster showed reciprocal and coordinated role engagement. Both members alternated between being the Experimenter and Recorder, demonstrating frequent role exchange (f = 5–6) and nearly symmetrical interaction frequencies between group members (A → B and B → A). This pattern reflected mutual contribution and shared regulation, indicating that both partners actively participated in experimentation and documentation. (2) Dominant Pattern. Groups in this cluster exhibited a fixed role characteristic, where one member (A) consistently acted as the Leader or Experimenter, while the partner (B) primarily took the Recorder or Observer role. Role exchange occurred infrequently (f = 1–2), and interaction flows were asymmetric, with more messages or actions initiated by the dominant member, for example, the frequency of A → B (f) is more than B → A (f) in group 1. From the observation, we can find that role interactions in this pattern were predominantly unidirectional, with the Experimenter operating the AR system and reporting findings to the Recorder, showing an imbalanced structure and static task division. (3) Passive Pattern. This cluster featured low engagement and minimal coordination. Interaction and communication between members were minimal. One member consistently performed both the Experimenter and Recorder roles, while the other remained a passive observer or peripheral participant, showing limited initiative or response, which is a highly unbalanced and ineffective collaborative structure.

Figure 2

The Role Exchange Dynamics Over Time



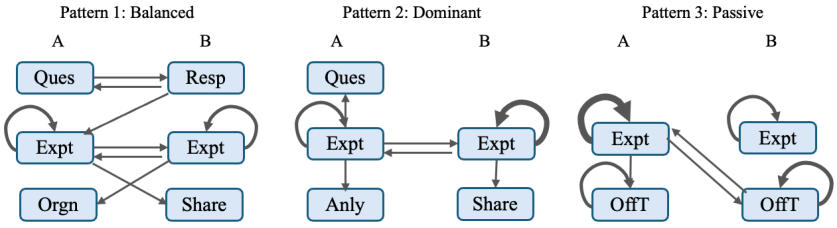
To further understand the interactive behaviors between group members, we conducted sequential pattern mining to examine the temporal structures of roles' actions. This analysis revealed the most frequent behavioral transitions between partners. For example, the transition *A_Question → B_Respond (f = 24)* indicates that member A asked a question followed by member B responding, occurring 24 times across the dataset. The top 10 frequent sequences were visualized in Figure 3. Dyads in the Balanced pattern demonstrated symmetrical collaboration and mutual regulation. They frequently engaged in bidirectional actions such as *Question → Respond* exchanges and *Experiment → Experiment* transitions. Moreover, *A_Experiment → B_Share* and *B_Experiment → A_Organization* sequences reflected reciprocal knowledge co-construction and shared responsibility for task progression. In the Dominant pattern, one member (A) consistently initiated *Question–Experiment–Analyze*

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sequences, while the partner (B) mainly followed with *Experiment–Share*, indicating a leader–follower dynamic. The excerpt below illustrates a typical example of this pattern. In contrast, the Passive pattern exhibited sparse and fragmented interaction, dominated by *Experiment–Off-task* transitions and lacking other task-related behaviors. This suggests that these dyads were frequently disengaged from the inquiry process and demonstrated limited regulatory coordination.

Figure 3

The Visualization of Top Sequential Patterns of Each Pattern



Note. Ques=Question, Resp=Respond, Expt=Experiment, OffT=Off Task, Orgn = Organization

Group 6-A: Then how do we make orange? (Observe the experiment) (Question → Experiment)

Group 6-B: Maybe we can control the intensity? Brighten the red light. (Experiment → Share)

Group 6-A: (Operates the tablet) No, that's not working (Experiment → Analyze)

Group 6-B: Since it lets you click "+" or "–". (Experiment → Share)

Group 6-A: Oh! Nice! It worked!

Learning outcomes

A one-way ANOVA was conducted to compare students' scientific knowledge across the three patterns at both pre- and post-test. No significant differences were found at the pre-test, indicating comparable baseline knowledge levels. At the post-test, however, significant group differences emerged ($F = 5.03$, $p = .009$, $\eta 2 = 0.12$). Post-hoc comparisons revealed that students in the balanced (M = 71.47) and dominant patterns (M = 63.32) outperformed those in the passive pattern (M=59.17). No significant difference was observed between the balanced and dominant groups ($p > .05$). This suggests that active participation and task-focused collaboration, regardless of whether balanced or dominated, are associated with greater knowledge gains compared to disengaged collaboration.

Discussion and conclusion

This study identified three distinct role interaction patterns: Balanced, Dominant, and Passive, that emerged during AR-based collaborative inquiry. Dyads in the Balanced pattern exhibited high equality and mutuality, frequently engaging in bidirectional *Question–Respond–Experiment–Share* sequences and flexible role exchanges. The Dominant pattern showed moderate equality and mutuality, where one member consistently led task execution while the partner followed. Although these dyads displayed dominant roles and more unidirectional interactions, their outcomes were comparable to those of the Balanced pattern. This suggests that dominant or leader–follower structures do not necessarily impede learning. Prior work indicates that certain emergent roles can support productive collaboration by structuring interaction and maintaining task focus, even when participation is uneven (Saqr et al., 2024). For instance, in Group 6, both members contributed comparably through verbal exchanges, resulting in smooth collaboration. This pattern resembles the "expert–novice" structure, which, alongside the "collaborative" pattern, has been recognized as an effective form of dyadic interaction (Storch, 2002). Finally, Passive groups scored low on both dimensions, showing limited engagement and minimal task-related coordination, suggesting weak regulation and frequent disengagement. Future instructional research should focus on this pattern by designing scaffolds that promote meaningful interaction and sustained engagement among less active groups.

Overall, this study advances understanding of how role interaction unfolds in immersive learning environments and how role dynamics shape collaborative outcomes. The findings emphasize that balanced participation, mutual responsiveness, and dynamic role exchange are critical for fostering high-quality collaboration in AR-based inquiry. Although dominant patterns do not always impede learning, ensuring equitable participation remains essential. Future work should incorporate multimodal data (e.g., gestures, gaze, and speech) and explore adaptive scripting or AI-based scaffolds to support mutual regulation and prevent dominance or passivity in immersive collaborative learning environments.

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