[DC] Exploring Behavioral Dynamics to Enhance Collective Intelligence in Virtual Environments

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ABSTRACT

Collective intelligence (CI) is a predictive measure of a group's ability to perform a wide variety of tasks. It is an essential concept for understanding team dynamics and enhancing team performance. While extensively studied in traditional environments such as face-to-face settings or online interactions, CI remains underexplored in immersive Virtual Reality (VR). This thesis has three goals: (1) to analyze how CI manifests in VR through verbal and non-verbal indicators, (2) to design real-time feedback systems that enhance CI in VR environments, and (3) to apply these findings to immersive educational platforms to improve collaboration and learning.

Index Terms: Collective intelligence, Virtual reality, Learning, Multimodal interaction, Transactive Memory System, Feedback

1 INTRODUCTION

1.1 An objective measure of Collective Intelligence

The concept of Collective Intelligence (CI) was introduced by Woolley et al. [12] in analogy with individual intelligence. They defined CI as a predictive measure of team performance across various tasks. They identified a single factor (*C-factor*) as a measure of CI, which accounted for over 40% of the variance in team performance. CI showed a weak link to individual intelligence but correlated strongly with team members' average social sensitivity and the proportion of women in the team. Subsequent studies confirmed its robustness in diverse contexts, including computer-mediated communication [4] and online gaming [7].

A meta-analysis by Rield et al. [10] of 22 studies involving 1356 teams found a strong relationship between the C-factor and team collaboration processes, identifying three predictors: **Collective effort** (i.e., the sum of individual efforts for all tasks), **Skill Congruence** (i.e., the relationship between members' skills and efforts for each task), and **Strategy** (i.e., the use of a strategy adapted to task performance). These factors significantly predicted CI during team interaction. Additionally, CI correlated with verbal interaction synchrony [11] and learning speed [1], highlighting their relevance to effective collaboration.

These empirical contributions provide insights into the mechanisms underlying the emergence of CI and the essential elements for effective collaboration within a team. However, despite their validation in traditional and computer-mediated environments, their applicability and reliability in immersive virtual reality contexts remain insufficiently explored. To bridge this gap, we draw on the well-established Transactive System Model for Collective Intelligence (TSM-CI) framework as a theoretical lens to investigate how CI may develop in VR—provided that the TSM-CI concept can indeed be observed in such environments through the *C-factor* measure. Below, we present an overview of the TSM-CI framework and discuss its relevance to our study.

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1.2 TSM-CI Framework

Transactive Memory System (TMS) refers to a team's distributed understanding of each member's skills and knowledge, allowing efficient coordination by enabling members to know who possesses specific expertise [8]. In 2003, Lewis highlighted three critical components of TMS: **Coordination** (smooth team action), **Credibility** (trust in members' expertise), and **Specialization** (task-specific expertise). These dimensions are commonly assessed through a 15-item Likert-scale questionnaire [8]. Recent research [3] linked TMS dimensions to non-verbal cues, such as head orientation, speaking turn distribution, and team arrangement, showing their impact on team performance. Another study [1] connected these measures to the C-Factor, highlighting their importance for understanding and describing CI.

Building on TMS theory, Gupta et al. [5] posited that an intelligent system is characterized by three fundamental functions: memory, attention, and reasoning processes. They expanded the model by introducing three socio-cognitive systems: Transactive Memory Systems (TMS) for managing dispersed knowledge, Transactive Attention Systems (TAS) for coordinating attention, and Transactive Reasoning Systems (TRS) for aligning collective goals. They argued that these systems' emergence and mutual adaptation provide the necessary framework for CI development, enabling teams to handle complex environments. This framework connects cognitive processes vital for CI with empirical indicators identified in prior CI studies.

1.3 The Potential of Virtual Reality for CI Enhancement

Virtual Reality (VR) offers a powerful platform for studying and enhancing CI, providing a controlled, immersive environment where team dynamics can be closely monitored. VR enables precise tracking of non-verbal indicators, such as gaze alignment, head orientation, spatial proximity, and turn-taking, which are critical for understanding group cohesion, leadership patterns, and engagement levels [2, 6]. These metrics can be used to observe collaboration and TMS components [3] and provide real-time, data-driven feedback to improve team processes. Feedback systems can fix issues like one person dominating or others not participating enough by helping teams work more fairly and effectively. This ability to both watch and improve teamwork makes VR a useful tool for improving CI in learning, training, and teamwork [9].

1.4 Research Questions

In the context of my PhD, I will explore the theoretical framework of TSM-CI and analyze team process indicators alongside verbal and non-verbal behaviors observed in teams. This work seeks to address the following research questions:

- **RQ1**: **a.** What behavioral cues, including verbal and non-verbal indicators, can be used to estimate a team's level of Collective Intelligence in VR? And **b.** How do these cues differ from those in PC-based environments?
- **RQ2**: How to design a VR environment to enhance Collective Intelligence of a team?

By investigating these questions, this research aims to deepen our understanding of CI dynamics and the potential of VR as a tool for monitoring and fostering CI in collaborative settings.

2 Proposed Methodology

This research unfolds in two phases: first, defining and validating objective CI measures tailored to VR, examining the transferability of the C-factor and the effects of interaction frequency and quality. The second phase applies these measures to refine team performance and feedback systems. Through iterative theoretical and empirical work, the study aims to establish VR as a robust platform for studying and enhancing CI in collaborative settings.

2.1 Behavioral Collaborative Dynamics in VR

Currently, in the first year of the PhD, we have been focusing on RQ1. We are conducting a behavioral analysis in VR to identify and quantify the multi-modal indicators of CI in immersive environments. Unlike traditional settings, VR offers unique affordances, such as spatial dynamics and embodied interactions [9]. This makes it a compelling environment to study the interactions between behavior and CI. The indicators studied are derived from prior research on team dynamics [2, 3, 6] and include:

- **Head Orientation and Gaze Patterns**: Indicative of shared attention, engagement, and leadership dynamics, these are precisely tracked via VR headsets.
- **Vocal Interaction Patterns**: Including turn-taking, interruptions, and pauses, these reflect participation equity and communication flow.
- **Spatial Proximity and Arrangement**: The positioning and movement of avatars provide insights into social cohesion, dominance, and disengagement.
- **Gestural/Postural Cues**: Behaviors like nodding or pointing reveal agreement, focus, and collaboration dynamics.

To validate these indicators, a longitudinal study is being conducted with engineering students collaborating on discipline-specific tasks in both PC-based and VR-based conditions. Teams adopt interdependent roles designed to foster coordination. The evaluation focuses on task performance, measured by adherence to constraints, time efficiency, and completion rates; collaboration quality, assessed through behavioral indicators tracked in VR; and Collective Intelligence, quantified using validated C-factor tests and correlated with behavioral data. We hypothesize a positive correlation between the C-factor and task performance, that non-verbal cues predict CI, and that CI improves across sessions in both VR and PC conditions. Differences in these cues remain exploratory, offering a comparative dataset.

2.2 Developing Feedback-Driven Interfaces

The second part of the PhD will focus on RQ2 by integrating the behavioral indicators into VR interfaces that provide real-time feedback. The system could highlight participation imbalances or guide attention to enhance coordination. Different forms of feedback will be explored, such as visual cues (e.g., a color gradient representing speaking time), auditory prompts, and multimodal feedback.

3 Conclusion

This research extends the TSM-CI framework into VR, deepening our understanding of how collective intelligence emerges and operates in immersive environments. The findings have theoretical and practical implications, including the design of immersive educational platforms that enhance team performance, foster collaboration, and improve learning outcomes. By integrating theoretical insights with multi-modal behavioral analysis and feedback systems, this work advances both the development of VR tools and the broader comprehension of CI in dynamic, interactive settings.

3.1 Questions for Doctoral Consortium

- **Indicator Validation**: How can the multi-modal indicators identified in this research be rigorously validated across diverse team contexts and tasks?
- **Feedback System Design**: What strategies can be employed to ensure that real-time feedback systems are both effective and non-disruptive in VR collaborations?

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