

Epistemic Network Analysis of Critical Thinking in Digital Game-Based Learning

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Abstract: Two major issues are identified in current research on critical thinking: (1) an over-reliance on outcome-based assessment and (2) limited methodological approaches for examining relationships among cognitive processes during learning. This study proposes the use of Epistemic Network Analysis (ENA) as a quantitative analytic approach to address these limitations. A virtual reality-based digital game-based learning environment is designed to capture students' behavioral data during problem-solving activities. Critical thinking is operationalized through multiple dimensions, including inference, interpretation, and evaluation. ENA is used to model how these dimensions co-occur and form connected patterns during learning. The proposed framework provides a process-oriented method for assessing critical thinking and examines how cognitive components are structurally connected during learning.

Keywords: Critical thinking, digital game-based learning, epistemic network analysis

1. Introduction

Critical thinking has been widely studied in education. Its assessment remains primarily focused on learning outcomes rather than underlying reasoning processes (Facione, 1990; Zhang et al., 2025). Limited empirical evidence explains how critical thinking develops during learning activities. Existing research also exhibits methodological limitations in examining higher-order thinking. Many studies rely on frequency-based or sequence-based analyses of learner behaviors. Although these approaches provide descriptive information, they do not adequately capture relationships among multiple cognitive processes that may occur simultaneously (Geng et al., 2024). To address these issues, this study proposes a process-oriented approach using Epistemic Network Analysis (ENA). ENA examines how cognitive components are linked based on how they co-occur during learning activities (Shaffer et al., 2016). This study situates the analysis within a virtual reality-based digital game-based learning environment, where learners engage in interactive problem-solving tasks that generate observable behavioral data.

2. Epistemic Network Analysis for Assessing Critical Thinking

Recent research on critical thinking has identified a continuing challenge in its assessment. While critical thinking has been widely studied, most existing approaches emphasize outcome-based measures, focusing on final performance rather than the underlying reasoning processes. As a result, limited empirical evidence explains how different components of critical thinking develop and interact during learning. A second issue concerns the methodological approaches used to examine higher-order thinking. Many studies rely on frequency counts or sequential analyses of observed behaviors. Although these approaches provide useful descriptive information, they are limited in capturing the relationships among multiple cognitive processes that may occur simultaneously during learning activities.

Epistemic Network Analysis (ENA) has been proposed as a methodological approach to address these limitations. Originally introduced by Shaffer (2009), ENA was designed to

assess complex learning by modeling the relationships among knowledge, skills, and cognitive processes within a given context. Rather than treating these elements as independent variables, ENA represents them as interconnected components within a network structure. Subsequent work by Shaffer et al. (2016) further developed ENA as a quantitative analytic technique. In this approach, coded behavioral data are used to identify co-occurrences among predefined categories. These co-occurrences are then transformed into network models representing the strength of connections among cognitive elements, allowing both visual representation and statistical comparison across groups.

An important feature of ENA is its reliance on theory-driven coding schemes. Shaffer and Ruis (2017) emphasize that the validity of ENA depends on clearly defined constructs that reflect target learning processes. In the context of critical thinking, these constructs typically include dimensions such as inference, interpretation, and evaluation. By mapping observed behaviors to these dimensions, ENA enables analysis of how different aspects of reasoning are integrated during learning. The methodological rigor of ENA is supported by its mathematical foundations. Bowman et al. (2018) demonstrate that ENA employs normalization and dimensional reduction techniques to generate comparable network representations across participants. This ensures that differences in network structures reflect variations in cognitive organization rather than differences in activity levels.

In addition, recent reviews indicate increasing adoption of ENA in educational research. Andrist et al. (2025) report that ENA has been applied to analyze complex learning processes by combining qualitative coding with quantitative modeling. These studies suggest that ENA is particularly suitable for examining higher-order thinking, where learning outcomes depend on the coordination of multiple cognitive processes. Overall, ENA provides a systematic approach for assessing critical thinking as a structured set of relationships among cognitive components, addressing limitations of traditional assessment methods by focusing on how reasoning processes are organized and interact during learning.

3. Research Design and Methodology

This study investigates whether a process-oriented analytic approach can examine the structure of critical thinking during learning. It explores how dimensions of critical thinking are interconnected and whether these relationships vary across learners. The study examines differences in critical thinking behaviors, structural connections among dimensions, and variations in cognitive organization across performance levels. A virtual reality-based digital game serves as the instructional environment. Learners engage in problem-solving tasks requiring information gathering, hypothesis formation, and decision-making. Data collection includes system-generated interaction logs, decision-making records, and time-stamped behavioral sequences, providing observable indicators of learners' cognitive processes during gameplay. Learner performance level and task conditions are considered independent variables, while the network structure of critical thinking (measured by ENA) serves as the dependent variable. Critical thinking is operationalized through inference, interpretation, evaluation, recognition of assumptions, and inductive/deductive reasoning. The analysis involves coding behavioral data, segmenting data into meaningful units, identifying patterns of co-presence, and constructing network representations that capture relationships among cognitive components. A normalization process is applied to account for differences in activity levels, and network structures are compared across groups, enabling both visualization and statistical comparison of these structures.

This proposed study will involve students recruited from elementary schools. Prior to commencement, parental consent will be secured, and a brief survey will be administered to assess participants' prior experience with digital gaming and virtual reality. The research procedure will consist of an initial briefing phase followed by a formal experimental phase. During the briefing, participants will receive a project overview, basic instructions on operating

the VR equipment, and essential safety guidance. In the experimental phase, participants will engage with the VR-based digital game in a classroom setting, with sessions scheduled according to curriculum arrangements and equipment availability. Due to resource constraints, participation will be organized in small groups within a designated timeframe. Throughout the study, system-generated behavioral data and screen recordings will be collected for analysis. All necessary ethical protocols will be followed, with appropriate consent obtained for the use of learning process data and student recordings.

4. Expected Results and Contributions

It is expected that ENA will identify distinct patterns of connections among critical thinking dimensions. Learners with higher performance levels are expected to demonstrate more integrated network structures, reflecting stronger relationships among reasoning processes. This study contributes by examining critical thinking as an evolving process rather than a final result and demonstrates the applicability of ENA in analyzing cognitive behaviors in immersive learning environments.

5. Discussion and Conclusion

The proposed approach addresses limitations in current assessment methods by focusing on relationships among cognitive components. This allows examination of how critical thinking is organized during learning. The use of a virtual reality-based environment enables the collection of behavioral data, supporting analysis of learning processes. Future work will involve empirical validation, refinement of coding schemes, and examination of additional variables influencing cognitive structure. This study proposes the use of Epistemic Network Analysis as a process-oriented method for assessing critical thinking. By modeling relationships among cognitive components, ENA provides an approach to understanding how reasoning develops during learning. This work establishes a foundation for future research.

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