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Critical Thinking as a Dynamic System: Tracking Nonlinear Development through Reading Study Worksheets in Elementary Science

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Abstract: This study applies Dynamic Systems Theory and the moving min-max graph to analyze the nonlinear development of critical thinking skills in elementary science education. Based on an eight-session reading worksheet intervention with 49 fifth-grade students, the study reveals three-stage trajectories, four types of learner behavior, and asynchronous development across critical thinking dimensions. This process-oriented approach offers a significant departure from traditional pre-post measurement paradigms.

Keywords: critical thinking, dynamic systems theory, science education, reading study worksheets, learning analytics

1. Introduction

Traditional developmental assessment measures, such as gain scores, often focus on overall changes in outcomes while neglecting the complexity and dynamics inherent in the developmental process. These metrics fail to capture the developmental range and variability of individuals at each time point—a critical oversight, as such variability may contain key transition points. Within science education, where critical thinking, recognized as a core 21st-century skill, develops through iterative engagement, this limitation is problematic. Reducing critical thinking development to a linear pre-post comparison fundamentally misrepresents its nonlinear trajectory.

Dynamic Systems Theory (DST) addresses this gap by positioning variability as a fundamental indicator of development, offering a transformative perspective by conceptualizing cognitive development as a complex, self-organizing process characterized by instability and phase transitions (Thelen & Smith, 1994). Through visualization techniques like the moving min-max graph (van Geert & van Dijk, 2002), DST enables researchers to detail the fluctuation range and variability of individuals at different measurement points, revealing the development trend and identifying critical transition points.

Critical reading, which demands an understanding of both content and context (Comber & Nixon, 2011), provides a vital foundation for fostering critical thinking in elementary science. This study uses structured science reading worksheets with stepped questions to explore the dynamics of CT development from a dynamic perspective. It shifts the focus from "how much change occurs" to "how change unfolds," empowering educators to decode the complexity of students' thinking processes.

2. Literature Review

2.1 Dynamic Systems Theory

Dynamic Systems Theory (DST) offers a theoretical framework for understanding learning as a complex, nonlinear, and self-organizing system. Many elements of learners' differences constitute a complex system. Development is not proportional to input; small changes can trigger significant shifts, and progress can regress or plateau (Granic et al., 2003). Self-organization refers to the process by which a system spontaneously forms an ordered structure through the interactions of its internal elements without external directives.

The states of a complex system are not unique. An attractor refers to a stable state toward which a system naturally evolves and tends to remain. A repellor refers to an unstable state that the system tends to move away from (Hollenstein, 2013). Phase transitions mark significant shifts between these states, often triggered by learning experiences and observable as periods of heightened variability in performance.

2.2 Critical Thinking in Science Education

Definitions converge on Critical Thinking (CT) as higher-order, purposeful thinking (Ennis, 1987; Facione, 1990), encompassing both cognitive skills and affective dispositions (Facione, 1990). This study focuses on the cognitive skill dimensions outlined in the Delphi Report, specifically interpretation, analysis, evaluation, inference, and explanation.

Cultivating CT in science education is crucial, given its unique demands for evidence-based reasoning and skeptical inquiry. Strategies often involve engaging with scientific texts. In College, interventions focus on critical analysis of primary literature (Fischer, 2021) or the C-QRAC collaboration scripts (Lee, 2015). In secondary, strategies include analyzing science-based news reports (McClune & Jarman, 2010), newspaper articles (Oliveras et al., 2013), and higher-order thinking tasks (Miri et al., 2007). Research at the elementary level is sparse, though science-based reading expands instructional time for deeper inquiry (Romance & Vitale, 1992), and concept mapping shows promise for skill development (Akinoglu, 2013). In conclusion, a gap exists in understanding the dynamic and nonlinear development of CT skills in young learners and how specific tools, such as worksheets, facilitate this process over time.

2.3 Reading Study Worksheets

Reading study worksheets are instructional tools that guide students through text by providing structured tasks. While prevalent in language arts (Anwar et al., 2020; Haswani et al., 2023), the use of these approaches in science, especially elementary science, is less explored. Emerging evidence suggests their efficacy in improving scientific explanation and confidence in junior high (Ikeda et al., 2023) and critical analysis skills in college (Fischer, 2021). However, studies typically rely on pre-post designs, failing to capture the dynamics of how worksheet-guided activities influence CT skill emergence and stabilization on a moment-to-moment and session-to-session basis.

3. Research Questions

Guided by DST, this study focuses on the development of CT skills in science for elementary students by using reading study worksheets. The research questions are as follows:

1. What is the nonlinear developmental trajectory of critical thinking skills in elementary school students guided by science reading study worksheets?
2. Is there consistency in the effects of students' critical thinking skills being influenced by reading study worksheets?
3. Is there consistency in the development of the dimensions of critical thinking skills among elementary school students?

4. Methods

4.1 Participants

The participants consisted of 52 fifth-grade students from an elementary school in Sichuan Province, China, with ages ranging from 10 to 11 years and a gender ratio approximating 1:1. Informed consent was obtained from all participating students and their teachers. Due to 1-2 absences by 3 students, 49 valid data points concerning the development of CT skills were included, which aligns with the requirement of DST for observing the entire process.

4.2 Research Procedure

The procedure was structured into two sequential phases to investigate the development of CT skills through science reading interventions. Each session lasted 30 minutes and took place once a week. Phase 1 (Sessions 1-2) focused on establishing baseline performance. Students engaged in unstructured reading of science articles without worksheet guidance, allowing researchers to capture initial skill levels in interpretation, analysis, evaluation, inference, and explanation. During Phase 2 (Sessions 3-8), participants transitioned to structured reading activities guided by stepped-question reading study worksheets.

4.3 Research Tools

The reading study worksheets were developed using literature-based adaptation, pilot testing, and expert validation. Every question was mapped to one of the five cognitive dimensions defined by the Delphi Report and then adapted from validated instruments such as A Test of Science Critical Thinking for fifth-grade students (Mapeala & Siew, 2015). Then, a pilot study was conducted with 15 fifth-graders from a parallel class; students thought aloud while completing the worksheets. Feedback indicated some items needed to be simplified in scientific terms or replaced due to overly advanced concepts.

The reasonableness of the worksheets' content and evaluation criteria was validated through an expert review method. Three reviewers rated each item's relevance to its appropriateness of the 5-point rubric (0 = no understanding, 5 = sophisticated, context-rich response). Mean ratings were 4.47 for interpretation, 4.22 for analysis, 4.00 for evaluation, 4.14 for inference, and 4.22 for explanation. All ratings were 4.0 or higher on a 5-point scale, confirming that the worksheets and criteria are theoretically grounded and empirically refined.

4.4 Data Analysis Methods

DST provides unique analytical methods, with the moving min-max graph as a time-series visualization tool (van Geert & van Dijk, 2002). The moving min-max graph is built in three steps. First, set a moving window (e.g., 8 data points) based on the data's time structure. This window slides through the dataset, each time excluding the oldest point from the previous window and adding the following new point. Second, for each window, calculate the minimum and maximum values of the target variable. Third, plot these minimum and maximum values over time—their vertical span forms a bandwidth, showing variability within each window. This technique shows the data using the bandwidth of observed scores.

In this study, three scientific readings were used as a moving window, and the data from 8 measurements were divided into 6 windows, e.g., (t1, t2, t3), (t2, t3, t4), ..., (t6, t7, t8). To visualize the entire 8-session trajectory, the min and max values for the first window (sessions 1-3) were assigned to sessions 1 and 2, and the min and max values for the last window (sessions 6-8) were assigned to sessions 7 and 8. This allows the moving extrema lines to span the full x-axis alongside the total score line.

The visual patterns of the min-max graph provide crucial insights into the learner's cognitive state dynamics. A narrowing bandwidth (decreasing vertical distance between min and max lines) suggests the system is stabilizing and may be approaching or residing within the basin of an attractor state. A widening bandwidth suggests instability and can be a sign that the system is in a transient state, potentially moving away from a repellor or undergoing a phase shift.

5. Results

5.1 Nonlinear Developmental Pathways

Analysis of total score-moving min-max graphs for 49 participants revealed two key patterns in critical thinking development. First, an overall upward trajectory was observed across sessions. Second, the process was characterized by significant nonlinear fluctuations, as 40 participants exhibited multiple performance peaks, specifically 37 with two peaks and 3 with three peaks, while only 9 showed minimal fluctuations with zero or one peak.

Cluster analysis using between-groups linkage on total scores from eight sessions demonstrated a three-stage developmental trajectory. Readings 1-2 formed a cluster representing initial sessions without worksheet intervention. Readings 3-5 formed a cluster characterized by upward fluctuations and the emergence of the first peak following the implementation of the worksheet. Readings 6-8 formed a cluster where skills stabilized despite continued fluctuations, resulting in subsequent peaks. This segmentation confirms a nonlinear developmental pattern initiated by pedagogical intervention.

5.2 Individual Differences and Classification

Participants were classified into four distinct developmental profiles based on a combination of cluster analysis and the number and timing of performance peaks.

Group 1 is characterized by three performance peaks. This group demonstrated lower performance in Reading Sessions 1-2, significant fluctuations in Sessions 3-6, and higher performance in Sessions 6-8. The moving extrema gap exhibited an increase-decrease trend, reflecting that fluctuations in students' CT levels first intensified and then diminished. According to DST, this fluctuation pattern suggests that the participants experienced a repellor state. These students exhibit highly active cognitive development. Their critical thinking is readily stimulated by interventions and responds rapidly, classifying them as efficient learners.

Group 2 exhibited two peaks, in Sessions 3 and 5. The moving extrema gap showed a decrease-increase trend, reflecting reduced then amplified fluctuations. This suggests that the participant experienced an attractor state. These students' thinking stabilizes quickly after an initial rapid improvement, and they adapt to the guidance provided by the reading worksheets.

Group 3 also exhibited two peaks, around Sessions 3 and 6/7. The moving extrema gap displayed a decrease-increase-decrease trend, pointing to an early attractor and a later repellor. These students require a longer period of accumulation for cognitive development, with intervention effects showing delayed results. Comprising the majority of participants, they represent the common trajectory that requires sustained practice to overcome thinking bottlenecks.

Group 4 showed minimal fluctuation, manifesting as either a single peak or a steady rise. Despite lacking clear peaks, the moving extrema gap still demonstrated a trend of decrease-increase-decrease, implying weak but detectable attractor-repellor dynamics. Correspondingly, the growth of these students' CT was slow and incremental, consistent with a more passive learning mode.

5.3 Asynchronous Development Across Dimensions

This study creates dimensional moving min-max graphs to examine how each dimension develops. Participant 51 from Group 3 (see Figure 1) was selected for detailed presentation as it exemplifies the complex interplay of attractor and repellor states within a single system, a characteristic feature observed in this largest group. Interpretation revealed decreasing-increasing trends with a marginally narrowing extremum bandwidth between moving extremes, suggesting insufficient evidence for attractor or repellor states. Analysis revealed up-down-up-down fluctuations amid progressive bandwidth contraction, indicating probable attractor stabilization with extended tracking. In evaluation, performance oscillated up-down-up-down as bandwidth first decreased, then increased, then decreased again, indicating the presence of one attractor and one repellor. Inference followed an up-down-up pattern, with bandwidth changing by first increasing, then decreasing, then increasing, similarly suggesting state competition. Explanation featured up–down–up–down fluctuations, yet bandwidth steadily shrank toward zero, indicating the presence of a repellor and an attractor. In the 7th science reading, the two moving lines coincide, indicating precisely the attractor state.

In addition, cross-dimensional comparison revealed marked asynchrony. During Sessions 5-6, Participant 51 improved in evaluation while regressing in explanation, suggesting resource competition between dimensions. These asynchronous patterns underscore DST's principle of multidimensional self-organization, where subsystems interact asynchronously to shape holistic skill development.

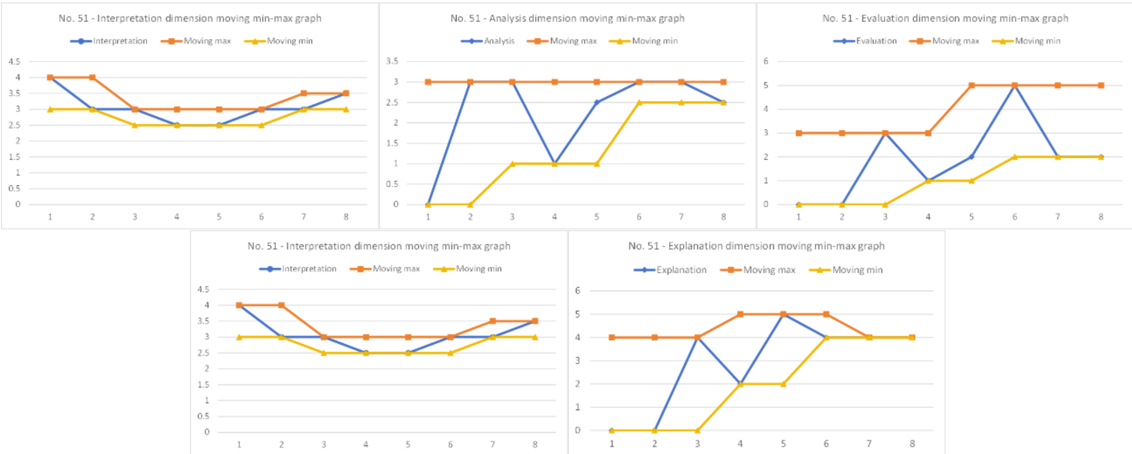

Figure 1. Moving Min-Max Graphs for Five Dimensions of Critical Thinking Skills (No.51).

Similar analyses for participants from the other three groups consistently revealed that students' overall attractor or repellor states are not equal to the simple sum of their subdimension states. It demonstrates that developing critical thinking skills is not a consistent process across all dimensions, but rather a complex and dynamic one.

6. Discussion and Conclusion

This study applied Dynamic Systems Theory to explore the nonlinear development of CT skills in elementary science education through reading study worksheets. The findings revealed that CT development follows a three-stage trajectory (baseline, transitional fluctuation, consolidation) characterized by variability and asynchronous progression across dimensions. This confirms DST's premise that cognitive growth is a dynamic, self-organizing process marked by instability (Thelen & Smith, 1994).

Reading study worksheets effectively scaffolded CT skills, as evidenced by the overall upward trend. However, their impact varied across learners, yielding four developmental profiles: efficient learners, early stabilizers, late stabilizers, and passive learners. This heterogeneity may stem from individual differences in receptiveness, metacognitive strategies, and learning pace. Educators can leverage these profiles by using the moving min max graph to identify attractor and repellor states and deliver personalized interventions, including metacognitive prompts for unstable dimensions and challenging tasks for efficient learners.

Critically, CT dimensions developed asynchronously, reflecting system-level instability. Interpretation and Analysis stabilized early (Sessions 5-6), suggesting that foundational skills are easier to consolidate. Evaluation and Inference fluctuated until Session 7, indicating higher cognitive load in integrating concepts. Notably, many students exhibited cross-dimensional competition, mirroring DST's concept of resource redistribution within a complex system.

However, the 8-session intervention captured initial development but limited observation of long-term consolidation or skill transfer. Future studies should extend duration and investigate interactions between CT skills and dispositions.

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