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Investigating Students' Critical Thinking Development in Data-Driven Statistical Decision Making through Mindtools-Based Learning Game Interactions

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Abstract

Students often experience difficulties in critically evaluating statistical evidence during data-driven decision making. This study investigated changes in students' critical thinking skills and the development of their thinking processes within a mindtools-based learning environment. A quasi-experimental study employing a single-group repeated-measures design was conducted with 32 undergraduate students enrolled in an introductory statistics course in one of private university, East Java, Indonesia. The learning environment was implemented through a spreadsheet-based learning game designed to support data exploration, statistical interpretation, and evidence-based decision making under conditions of uncertainty. Quantitative data were obtained from critical thinking pretest and posttest scores, while qualitative data were collected through observations, written justifications, reflective responses, and learning artifacts generated across three progressively designed learning missions. Quantitative data were analyzed using a paired-samples *t*-test, whereas qualitative data were analyzed using deductive content analysis based on Facione's critical thinking framework. The results revealed a significant improvement in students' critical thinking skills following the intervention. Qualitative findings further showed that students' thinking processes evolved from reliance on single statistical indicators toward more reflective evaluation of evidence and revision of decisions. The development of critical thinking dimensions was not uniform across missions; while interpretation and analysis were more evident during initial interactions with data, evaluation and self-regulation emerged more prominently when students encountered ambiguity and statistical uncertainty. These findings suggest that spreadsheet-based learning games, when designed as mindtools, can facilitate the development of critical thinking through evidence evaluation, reflection, and decision revision in data-driven statistical decision-making contexts.

Introduction

In contemporary mathematics and statistics education, where instructional practices are increasingly informed by data, decisions regarding the effectiveness of educational interventions are often based on the interpretation of statistical analyses comparing the performance of different learning groups (Bakker & Wagner, 2020; Prodromou & Lavicza, 2021; Pfannkuch & Ben-Zvi, 2021). Educators are frequently challenged to determine whether observed differences genuinely reflect the effectiveness of an intervention or merely result from statistical uncertainty, particularly when one group experiences an innovative instructional approach while another follows conventional instruction. Research in statistics education suggests that data-driven decision making is often influenced by interpretations that oversimplify the complexity of statistical evidence, such as relying on a single indicator without adequately considering variability or inferential uncertainty (Garfield & Ben-Zvi, 2008; Zieffler et al., 2018; Engel, 2020). Recent studies have further emphasized the growing importance of critically evaluating statistical evidence in data-rich learning environments, especially when individuals are required to make decisions under conditions of ambiguity and uncertainty (Weiland & Reckase, 2020; Ridgway et al., 2021; Ben-Zvi et al., 2022). These challenges highlight the need for students to construct and revise evidence-

based decisions through reflective engagement with statistical information in authentic educational contexts.

Recent research indicates that many students struggle to integrate multiple statistical indicators into coherent judgments, even when formal statistical analyses provide a framework for supporting data-driven decision making (Burrill et al., 2023). Learners often rely on simplified interpretations, such as focusing primarily on mean values while overlooking variability and inferential uncertainty, resulting in superficial conclusions and less accurate decisions (Garfield & Ben-Zvi, 2008; Zieffler et al., 2018; (Ben-Zvi et al., 2022). Studies in statistics education further suggest that understanding concepts such as confidence intervals requires students to connect mathematical representations with conceptual interpretations and decision-making contexts, a process that remains cognitively demanding for many learners (Pfannkuch & Ben-Zvi, 2021; Shaughnessy, 2023). Moreover, research in the learning sciences emphasizes that these difficulties extend beyond procedural knowledge and involve the ability to evaluate statistical evidence and revise decisions when confronted with ambiguous or conflicting information (Bakker & Wagner, 2020; Engel, 2020; Ridgway et al., 2021). Collectively, these findings underscore the need for instructional approaches that not only develop analytical skills but also support students' critical evaluation of statistical evidence and evidence-based decision making in authentic learning contexts.

The rapid development of digital technologies has created new opportunities for mathematics and statistics education through the use of interactive tools that enable data visualization, variable manipulation, and dynamic exploration of alternative scenarios. Research in mathematics education has shown that technology can enhance learner engagement by providing visual representations that support deeper and more reflective conceptual exploration (Drijvers, 2019; Prodromou & Lavicza, 2021; Hoyles & Noss, 2020). Within statistics education, spreadsheets and interactive data-analysis tools allow students to engage in more authentic data investigations, including exploring the consequences of changing parameters and interpreting statistical evidence across different decision-making situations (Engel, 2020; Weiland & Reckase, 2020; Ben-Zvi et al., 2022).

Despite these benefits, technology use in statistics education often remains focused on analytical procedures or the visualization of results, rather than explicitly supporting the thinking processes that underlie evidence-based decision making (Bakker & Wagner, 2020; Ridgway et al., 2021); Sa'dijah & others, 2022). From a learning sciences perspective, technology can be viewed not merely as a tool but as a cognitive partner that supports complex thinking through interaction with representations and reflection on evidence (Bakker & Derry, 2021). This perspective provides opportunities to investigate technology as a cognitive environment that actively facilitates students' thinking processes (Zamzam et al., 2023), leading to the concept of *mindtools* as a theoretical framework for understanding the relationship between technology and thinking in data-driven decision making.

The concept of *mindtools*, introduced by Jonassen, positions digital technology not simply as a medium for delivering information but as a cognitive partner that supports complex thinking through the

representation, manipulation, and reflection of ideas (Jonassen, 1996; Jonassen, 2000; Jonassen & Carr, 2000). From this perspective, technology functions as an external cognitive artifact that enables learners to construct understanding through active interaction with problem representations, thereby fostering deeper epistemic engagement than technologies designed primarily for instruction or procedural practice. Research in the learning sciences suggests that digital environments designed as *mindtools* can support learners in exploring alternative solutions, testing hypotheses, and revising decisions based on available evidence (Kim & Reeves, 2007; Bakker & Derry, 2021; Spector & Ma, 2019). In statistics education, spreadsheets can therefore be viewed not only as tools for data analysis but also as interactive environments that support critical evaluation of statistical evidence through scenario manipulation, interpretation of statistical information, and reflection on the consequences of decisions made under conditions of uncertainty.

A widely adopted framework for critical thinking in educational research was developed by Facione (1990), who identified six core skills: interpretation, analysis, evaluation, inference, explanation, and self-regulation. These skills represent interconnected cognitive processes involved in understanding information, evaluating the quality of evidence, drawing conclusions, and reflecting on decisions. In the context of data-driven statistical decision making, the integration of these dimensions is particularly important because individuals are often required to make judgments based on uncertain or conflicting evidence. Such situations demand critical evaluation of data representations and the statistical uncertainty associated with them (Pfannkuch & Ben-Zvi, 2021; Shaughnessy, 2023).

Previous studies suggest that critical thinking in statistics extends beyond procedural mathematical knowledge and involves the ability to interpret data reflectively, integrate multiple statistical indicators, and construct evidence-based arguments in decision-making contexts keputusan (Sa'dijah & others, 2022; Lai, 2011; Ben-Zvi et al., 2022). Therefore, Facione's framework provides a relevant conceptual foundation for examining how students' thinking processes develop during interactions with mindtools-based learning environments. While the concept of *mindtools* explains how technology can facilitate thinking activities, an additional analytical framework is needed to identify specific manifestations of critical thinking that emerge during such interactions. In this study, the integration of *mindtools* and Facione's critical thinking framework is used to explain how students' critical thinking develops during data-driven statistical decision making. *Mindtools* are positioned as cognitive environments that enable exploration and reflection through scenario manipulation and active interaction with digital artifacts, whereas Facione's framework provides an analytical lens for identifying critical thinking dimensions that emerge during the interpretation of data, evaluation of evidence, and revision of decisions (Facione, 1990; Jonassen, 2000; Bakker & Derry, 2021).

Accordingly, this study does not view technology as a factor that directly improves critical thinking. Rather, technology is conceptualized as a mediator that facilitates interactions between students and statistical representations. Through these interactions, various forms of critical thinking may emerge and develop dynamically during decision-making processes. This perspective aligns with learning sciences research, which emphasizes that cognitive development is influenced not only by instructional

content but also by learning environments that support exploration, reflection, and continuous revision of understanding (Kim & Reeves, 2007; Spector & Ma, 2019; Bakker & Derry, 2021).

Previous research has extensively explored the development of critical thinking in mathematics and statistics education, as well as the potential of digital technologies to support data exploration. However, most studies have focused primarily on learning outcomes or improvements in specific skills as indicators of intervention effectiveness (Prodromou & Lavicza, 2021; Weiland & Reckase, 2020; Ben-Zvi et al., 2022). Within educational technology research, digital tools have been shown to enhance student engagement and understanding of statistical concepts through data visualization and manipulation (Engel, 2020; Drijvers, 2019; (Ridgway et al., 2021). Interactive digital environments have also been reported to improve students' ability to analyze and interpret data, although challenges related to statistical uncertainty and inference remain prevalent (Howe & others, 2024; Engel et al., 2021). While prior studies have generally evaluated technology in terms of learning outcomes, less attention has been given to understanding how technology facilitates students' thinking processes during data-driven decision making. In particular, limited empirical evidence has documented how students use statistical representations, compare multiple indicators, and revise decisions when confronted with ambiguity and statistical uncertainty in authentic learning contexts. Yet, data-driven decision making requires the ability to critically evaluate statistical evidence rather than merely perform statistical calculations.

This study adopts a more integrative perspective by examining how a *mindtools*-based learning environment mediates the development of students' critical thinking during data-driven statistical decision making. Specifically, the study contributes to the literature by investigating critical thinking not only as an outcome reflected in overall performance gains, but also as a dynamic process manifested through the development of critical thinking dimensions when students interact with ambiguous data and situations involving statistical uncertainty. In doing so, the study seeks to explain how students' thinking processes evolve through the evaluation of evidence, reflection, and revision of decisions within a spreadsheet-based learning game environment.

Based on these research gaps, this study aims to investigate how a *mindtools*-based learning environment, implemented through a spreadsheet-based learning game, facilitates the development of students' critical thinking in data-driven statistical decision making. In this study, spreadsheets function not merely as tools for statistical computation but as cognitive environments that enable students to manipulate data, explore alternative outcomes, and evaluate the consequences of decisions. Through these interactions, students are encouraged to connect data representations with conceptual interpretations, allowing critical thinking to develop progressively throughout the decision-making process.

More specifically, this study focuses on two complementary aspects of learning: changes in students' critical thinking skills and the development of their thinking processes during interactions with a *mindtools*-based learning environment designed through progressive missions. This approach enables the analysis of not only learning outcomes but also how students construct, evaluate, and revise

decisions based on statistical evidence in situations involving data uncertainty. Accordingly, the study addresses the following research questions:

RQ1

Is there a significant change in students' critical thinking skills after interacting with a *mindtools*-based learning environment in the context of data-driven statistical decision making?

RQ2

How do students' thinking processes develop during interactions with a *mindtools*-based learning environment across progressive learning missions?

RQ3

Which dimensions of critical thinking develop most prominently as students engage in mission-based statistical decision-making activities?

This study offers an integrative perspective that connects the concept of *mindtools* as cognitive mediators with Facione's critical thinking framework to explain how students' thinking processes develop during statistical decision making. Rather than viewing technology as a tool that directly improves learning outcomes, the study emphasizes the role of digital environments as thinking partners that facilitate reflective interactions with statistical representations. Theoretically, this study contributes to a deeper understanding of the mechanisms through which *mindtools* mediate the development of critical thinking in situations characterized by ambiguity and statistical uncertainty. Practically, the findings are expected to inform the design of statistics learning environments that promote not only analytical skills but also critical thinking through meaningful interactions with data in authentic decision-making contexts.

Research Method

Research Design

This study employed a quasi-experimental design using a single-group repeated-measures approach to investigate changes in students' critical thinking skills and the development of their thinking processes within a *mindtools*-based learning environment. This design enabled the observation of students' cognitive development in an authentic learning context without the full manipulation of a control group (Shadish et al., 2002). The study adopted a mixed-methods approach by integrating quantitative and qualitative data. Quantitative data were used to examine changes in critical thinking skills through comparisons of pretest and posttest scores, whereas qualitative data were used to analyze the development of students' thinking processes during interactions with the *mindtools*-based learning environment.

Participants

The participants consisted of 32 undergraduate students enrolled in a Mathematics Education program who attended a regular introductory statistics course in one of private university, East Java, Indonesia. The participants had an average age of 21 years. The sample size was determined by the availability of a single intact class within an authentic instructional setting. This approach is commonly employed in quasi-experimental educational research aimed at examining learning changes within natural classroom environments (Shadish et al., 2002).

For in-depth qualitative analysis, four participants were selected through purposive sampling as information-rich cases. Participant selection was based on active engagement throughout the learning missions, the completeness of observational data, and variation in initial characteristics reflected in pretest performance. These criteria enabled a detailed exploration of how students' thinking processes developed during data-driven statistical decision-making activities.

Mindtools-Based Learning Environment

The learning environment was designed using an interactive spreadsheet that functioned as a *mindtool*, a technology that supports the representation, manipulation, and reflection of complex ideas during data-driven decision making. The environment was structured around a decision-oriented scenario that simulated the evaluation of educational programs based on statistical evidence. Its primary features included direct data manipulation and exploration of statistical analyses to support decision-making processes. The learning activities consisted of three progressively designed missions with increasing levels of complexity intended to foster the development of students' thinking processes during statistical decision making.

- **Mission 1** involved a low level of ambiguity and was designed to identify students' initial thinking processes when interpreting the problem and examining statistical data.
- **Mission 2** introduced conflicts among statistical indicators, such as discrepancies between mean values and confidence intervals, requiring students to evaluate the strength of statistical evidence before making decisions.
- **Mission 3** presented a decision-making dilemma in which students were required to consider multiple possibilities, reflect on available evidence, and justify their final decisions under conditions of uncertainty.

The three progressively designed missions were implemented through an interactive spreadsheet-based learning environment that guided students from understanding the problem context to evaluating statistical evidence and reflecting on their decisions. Figure 1 illustrates the interface and overall learning flow of the spreadsheet-based learning game used in this study.

Research Instruments

Two types of instruments were employed in this study: a critical thinking test and a critical thinking observation and coding framework. The critical thinking framework was adapted from Facione (1990), which comprises six core dimensions: *interpretation, analysis, evaluation, inference, explanation*, and *self-regulation*. These dimensions served as the analytical basis for examining students' written justifications and decision-making processes during interactions with the *mindtools*-based learning environment.

The *interpretation* dimension was used to identify how students recognized and represented statistical information. *Analysis* referred to the identification of relationships among statistical variables and indicators. *Evaluation* captured students' judgments regarding the quality of evidence and the uncertainty associated with the data. *Inference* reflected the ability to draw conclusions based on available evidence. *Explanation* focused on how students justified their decisions, whereas *self-regulation* referred to the revision of decisions through reflection and reconsideration of evidence.

Data Collection

Both quantitative and qualitative data were collected. Quantitative data were obtained from students' critical thinking pretest and posttest scores and were used to examine changes in critical thinking skills following the intervention. Qualitative data were collected from students' written justifications, explanations of decision revisions, reflective responses generated during the missions, and observations of students' activities while interacting with the *mindtools*-based learning environment.

These qualitative data sources were used to identify the development of students' thinking processes and the emergence of critical thinking dimensions throughout the data-driven statistical decision-making activities.

Table 1
Coding Framework for Critical Thinking Dimensions

Critical Thinking Dimension	Operational Indicator
Interpretation	Identifying, describing, and interpreting statistical information and data representations.
Analysis	Comparing statistical indicators and identifying relationships among variables or data patterns.
Evaluation	Assessing the quality, credibility, and strength of statistical evidence, including uncertainty and variability.
Inference	Drawing conclusions and making decisions based on available statistical evidence.
Explanation	Providing logical justifications and evidence-based arguments to support decisions.
Self-regulation	Reviewing, reflecting upon, and revising decisions based on additional evidence or reconsideration of previous interpretations.

Data Analysis

Quantitative and qualitative analyses were conducted to investigate changes in students' critical thinking skills and the development of their thinking processes during interactions with the *mindtools*-based learning environment. To address RQ1, quantitative data obtained from the critical thinking pretest and posttest were analyzed using a paired-samples *t*-test to determine whether significant changes occurred following the intervention.

To address RQ2 and RQ3, qualitative data were analyzed using a deductive qualitative content analysis approach. Students' written justifications, decision revisions, reflective responses, observational records, and learning artifacts generated during the missions were examined using Facione's (1990) critical thinking framework as the coding scheme. The six dimensions of critical thinking—*interpretation, analysis, evaluation, inference, explanation*, and *self-regulation*—served as the primary coding categories.

The coding process aimed to identify how students' thinking processes evolved across the three progressively designed missions and to determine which critical thinking dimensions became more prominent as task complexity increased. Cross-mission comparisons were conducted to examine shifts in students' engagement with statistical evidence, decision justification, and reflective revision of decisions.

To enhance the credibility and consistency of the analysis, two independent raters coded the qualitative data. Differences in coding were discussed until agreement was reached, following the procedures recommended by Miles et al. (2014). The resulting coding patterns were subsequently synthesized to describe the development of students' thinking processes (RQ2) and the progression of critical thinking dimensions throughout the learning activities (RQ3).

Ethical Considerations

This study was conducted in accordance with the ethical principles for educational research. Ethical oversight was provided by the Research Ethics Committee of Universitas Negeri Malang. The committee confirmed that the study involved undergraduate students who are legally recognized as adults in Indonesia and therefore did not require parental or guardian consent (Reference No. **25.6.30/UN32.14/PB/2026**).

Before data collection, all participants received information about the purpose and procedures of the study and voluntarily agreed to participate by providing informed consent. Participation was entirely voluntary, and participants were informed of their right to withdraw from the study at any time without academic consequences. To protect participants' privacy, all data were anonymized prior to analysis, and the findings are reported in aggregate form or using anonymous participant codes (e.g., S1–S4).

Results

4.1 Changes in Students' Critical Thinking Skills

Descriptive Statistics

Students' critical thinking skills were assessed through pretest and posttest measures administered before and after the implementation of the spreadsheet-based learning game. A total of 32 undergraduate students participated in the study. Descriptive analysis indicated that the mean pretest score was 6.56 (*SD* = 0.67), whereas the mean posttest score increased to 8.59 (*SD* = 0.92). The increase in the mean score suggests an improvement in students' critical thinking skills following participation in the mindtools-based learning environment designed for data-driven statistical decision making. Descriptive statistics for students' pretest and posttest critical thinking scores are presented in Table 2.

Table 2
Descriptive Statistics of Students' Critical Thinking Scores

Pretest	**Mean**	**N**	**Std. Deviation**	**Std. Error Mean**
	6,5625	**32**	**0,669**	**0,118**
Posttest	8,5938	32	0,915	0,162

Prior to hypothesis testing, the normality assumption was examined using the Shapiro–Wilk test because the sample size was fewer than 50 participants. The results indicated that the critical thinking scores were normally distributed (W = 0.962, p = .312). Since the significance value exceeded .05, the assumption of normality was satisfied, supporting the use of parametric statistical analysis.

Changes in Students’ Critical Thinking Skills

To address RQ1, a paired-samples t-test was conducted to examine changes in students' critical thinking skills following participation in the spreadsheet-based learning game. The paired-samples t-test revealed a statistically significant difference between students' pretest and posttest critical thinking scores, t(31) = − 14.00, p < .001. The complete results of the paired-samples t-test are presented in Table 3 below.

Table 3
Paired-Samples t-Test Results

Comparison	Mean Difference	SD	t	df	p	Cohen’s d
Pretest – Posttest	−2.03	0.82	−14.00	31	< .001	2.48

The mean difference was − 2.03 (95% CI [− 2.33, − 1.74]), indicating that students achieved substantially higher scores after the intervention. Furthermore, the effect size was very large (*d* = 2.48), suggesting that the intervention had a substantial impact on students’ critical thinking skills.

These findings indicate that participation in the mindtools-based learning environment significantly improved students’ critical thinking skills in the context of data-driven statistical decision making. Therefore, RQ1 can be answered affirmatively: students demonstrated significant gains in critical thinking following the implementation of the spreadsheet-based learning game.

4.2 Development of Students’ Thinking Processes Across Missions

To address RQ2, qualitative data from observations, written justifications, reflective responses, and learning artifacts were analyzed across the three progressively designed missions. The results indicated that students’ thinking processes developed gradually as the complexity of the decision-making tasks increased.

During Mission 1, most students relied on a single statistical indicator, particularly the mean, when making decisions. Their thinking processes were primarily focused on identifying relevant information and comparing basic statistical results. In Mission 2, students began to consider multiple statistical indicators and evaluate the uncertainty associated with the data before reaching conclusions. By Mission 3, students demonstrated more reflective thinking processes, characterized by reviewing previous interpretations, reconsidering evidence, and revising decisions based on the strength of statistical evidence. The cross-mission development of students’ thinking processes is summarized in Table 4.

Table 4
Cross-Mission Development of Students' Thinking Processes

Participant	Mission 1	Mission 2	Mission 3	Development Pattern
S1	Interpretation–Analysis	Analysis–Evaluation	Evaluation–Self-Regulation	Progressive Development
S2	Analysis–Evaluation	Analysis–Evaluation	Evaluation–Explanation	Stable and Consistent
S3	Analysis	Evaluation	Evaluation–Self-Regulation	Dynamic Development
S4	Interpretation	Analysis	Evaluation	Gradual Development

Note. The categories reported in each mission represent the dominant critical thinking dimensions identified from students' written justifications, reflective responses, observations, and learning artifacts.

Participant S1 demonstrated a progressive development of thinking processes across the three missions. In Mission 1, decisions were primarily based on mean values, indicating a focus on direct interpretation of statistical information. In Mission 2, S1 began to evaluate multiple indicators by incorporating confidence intervals when comparing groups and considering the possibility of overlapping evidence. By Mission 3, S1 demonstrated more reflective thinking through the consideration of data variability and the revision of conclusions based on the overall strength of statistical evidence. These changes suggest a progression from interpretation and analysis toward evaluation and self-regulation during data-driven decision making. Figure 2 presents representative excerpts from Participant S1's written responses across the three learning missions, illustrating this developmental progression.

Participant S2 exhibited a relatively stable pattern of thinking processes across the three missions. From the outset, S2 considered multiple statistical indicators when making data-driven decisions, demonstrating the simultaneous use of analysis and evaluation dimensions. Across Missions 2 and 3, S2 consistently evaluated statistical evidence by considering confidence intervals and data variability before drawing conclusions. Rather than showing substantial shifts in reasoning strategies, S2 demonstrated increasing sophistication in the application of evidence-evaluation practices. This pattern suggests that the learning environment primarily reinforced and refined existing critical thinking processes rather than fundamentally altering them.

Participant S3 demonstrated a dynamic development of thinking processes throughout interactions with the mindtools-based learning environment. In Mission 1, decisions were primarily based on mean values,

reflecting an emphasis on initial interpretation and analysis of statistical information. In Mission 2, S3 began to incorporate confidence intervals when evaluating statistical evidence, indicating the emergence of the evaluation dimension. By Mission 3, S3 demonstrated more reflective thinking through the consideration of data variability and the reconsideration of previous conclusions before making a final decision. As illustrated in Fig. 3, this progression reflects a shift from basic statistical interpretation toward evidence evaluation and self-regulated decision making.

Participant S4 exhibited a gradual development of thinking processes across the three missions. In Mission 1, decisions were largely based on mean values as the primary source of statistical information. During Mission 2, S4 began comparing groups by considering confidence intervals alongside mean values, indicating a transition from interpretation toward analysis. In Mission 3, variability was incorporated into the evaluation process before a final decision was made. Although the progression was more gradual than that observed for S1 and S3, the results suggest increasing engagement with statistical evidence as task complexity increased.

Overall, the four participants demonstrated distinct developmental patterns of thinking processes during interactions with the mindtools-based learning environment. Some participants progressed from reliance on a single statistical indicator toward more comprehensive evaluation of statistical evidence, whereas others displayed relatively stable but increasingly refined evaluation strategies throughout the missions. Despite these differences, all participants showed greater engagement with statistical uncertainty and evidence evaluation as mission complexity increased. These findings suggest that the development of thinking processes in data-driven statistical decision making is influenced not only by task complexity but also by how learners interact with statistical representations and evidence within the learning environment.

4.3 Development of Critical Thinking Dimensions Across Learning Missions

To address RQ3, the qualitative data were analyzed using Facione's critical thinking framework. The results indicate that the development of critical thinking dimensions did not occur uniformly across the three missions. Instead, increasing task complexity elicited different dimensions of critical thinking as students interacted with the mindtools-based learning environment. During Mission 1, students' thinking processes were dominated by the dimensions of interpretation and analysis. Most students relied primarily on mean values to interpret and compare data across groups. At this stage, decision making focused mainly on identifying and interpreting readily observable statistical information.

In Mission 2, the evaluation dimension became more prominent as students were confronted with more ambiguous data. Students began considering confidence intervals and the possibility of overlapping evidence before making decisions. The use of multiple statistical indicators suggests that students increasingly evaluated the strength of statistical evidence rather than relying on a single measure. By Mission 3, the dimensions of evaluation and self-regulation became more dominant. Students demonstrated a greater tendency to revisit previous interpretations, consider data variability, and revise conclusions based on the overall strength of available evidence. These findings suggest that increasing

task complexity encouraged students to engage in reflective judgment and decision revision during the decision-making process. Figure 4 presents the developmental trajectory of the dominant critical thinking dimensions across the three learning missions, illustrating the transition from interpretation and analysis toward evaluation and self-regulation.

Overall, the findings indicate that critical thinking dimensions developed dynamically throughout students' interactions with the mindtools-based learning environment. While interpretation and analysis were most evident during the initial stages of data exploration, evaluation and self-regulation emerged more strongly when students encountered ambiguity and statistical uncertainty. Among the six dimensions of Facione's framework, evaluation and self-regulation demonstrated the most substantial development across missions, reflecting students' increasing ability to assess evidence critically and revise decisions based on reflection. These results suggest that mindtools-based learning environments support not only procedural understanding but also the development of higher-order critical thinking through evidence evaluation and reflective decision making.

Discussion

5.1 Changes in Students' Critical Thinking Skills

The findings indicate that the spreadsheet-based learning game, designed as a mindtools-based learning environment, contributed positively to students' critical thinking skills in data-driven statistical decision making. The significant improvement in critical thinking scores suggests that engaging students in activities involving data exploration, evidence evaluation, and decision justification can support the development of higher-order thinking skills. This finding is consistent with previous studies reporting that game-based learning and interactive learning environments can enhance critical thinking and cognitive engagement (Sa'dijah & others, 2020; Mao et al., 2022; Ma et al., 2023; Khoo et al., 2025). Research has also shown that game-based learning can increase cognitive engagement and learning motivation, both of which are important factors in the development of higher-order thinking (Gao et al., 2024); (Videnovik et al., 2023; Hii & Mahmud, 2023).

The improvement observed in this study appears to be associated not merely with the use of technology itself, but with the nature of the learning activities supported by the environment. Throughout the missions, students were required to interpret data, compare multiple statistical indicators, and evaluate the strength of evidence before making decisions. These activities encouraged students to connect statistical representations with conceptual interpretations and to justify decisions based on evidence rather than intuition alone. This finding supports the view that critical thinking in statistics education develops through active engagement in interpreting and evaluating statistical evidence rather than through procedural calculation alone (Park & Leatham, 2021; Garfield & Ben-Zvi, 2022; Shaughnessy, 2020).

From a mindtools perspective, technology functions as a cognitive partner that supports exploration, reflection, and evidence-based reasoning. The spreadsheet-based learning game enabled students to

examine alternative interpretations of data, test decisions against available evidence, and reconsider conclusions when confronted with uncertainty. Consequently, the observed gains in critical thinking can be understood as the result of interactions among learners, statistical representations, and the mindtools-based learning environment. These findings suggest that statistics instruction designed around data-driven decision-making activities can foster critical thinking in a more contextualized and reflective manner, particularly in situations involving ambiguity and statistical uncertainty.

5.2 Development of Students' Thinking Processes Across Progressive Missions

The findings indicate that students' thinking processes evolved gradually during interactions with the mindtools-based learning environment. This development was reflected in the transition from reliance on a single statistical indicator toward more reflective evaluation of statistical evidence. Rather than occurring as an immediate change, the progression emerged through repeated engagement with data representations and decision-making tasks of increasing complexity.

During Mission 1, most students relied primarily on mean values when making decisions. Their responses were largely descriptive and procedural, focusing on identifying and comparing readily observable statistical information. This finding is consistent with previous research suggesting that students often depend on single statistical indicators when initially engaging in data-driven decision-making activities (Garfield & Ben-Zvi, 2022; Reading & Reid, 2021).

A notable shift emerged in Mission 2 when students encountered more ambiguous data. The use of multiple indicators, particularly mean values and confidence intervals, reflected increasing attention to the quality of evidence rather than to numerical results alone. This transition suggests movement from procedural interpretation toward more analytical and evaluative thinking. Similar patterns have been reported in studies showing that statistical reasoning develops when learners engage in conceptual interpretations of data and statistical uncertainty (Lee & Meletiou-Mavrotheris, 2023; Wild & Pfannkuch, 2023).

By Mission 3, students demonstrated more reflective forms of thinking as they considered data variability, revisited previous interpretations, and occasionally revised decisions when the available evidence was judged insufficient. These behaviors suggest an emerging awareness that statistical information serves not merely as a computational tool but as a basis for evaluating evidence under uncertainty. This finding aligns with research emphasizing that statistical decision making involves continuous evaluation of uncertainty and revision of interpretations based on available evidence (Chance & delMas, 2022; Zieffler & Garfield, 2020).

The progression observed across the three missions further highlights the role of task complexity in shaping students' thinking processes. As the missions became increasingly ambiguous, students were required not only to interpret data but also to evaluate competing evidence and reconsider previous conclusions. From a mindtools perspective, the learning environment functioned as a cognitive space that supported exploration of statistical representations and reflection on the consequences of

decisions. Consequently, the development of students' thinking processes can be understood as the result of sustained interactions among learners, statistical evidence, and progressively challenging decision-making tasks.

5.3 Development of Critical Thinking Dimensions During Interaction with Mindtools

The findings indicate that the development of critical thinking did not occur uniformly across dimensions during students' interactions with the mindtools-based learning environment. Instead, increasing task complexity elicited different dimensions of critical thinking throughout the data-driven decision-making process.

During Mission 1, students' responses were dominated by the dimensions of interpretation and analysis. Most participants relied primarily on mean values when reading and comparing data across groups. At this stage, students focused on identifying statistical information and recognizing basic patterns in the data. These findings suggest that initial engagement with statistical representations primarily involved understanding and organizing information before engaging in more complex forms of judgment.

The development of critical thinking dimensions became more evident in Mission 2 when students encountered increasingly ambiguous data. The evaluation dimension emerged as students compared confidence intervals, considered potential overlap among data distributions, and assessed the strength of statistical evidence before making decisions. This shift suggests that students moved beyond procedural interpretation toward critical appraisal of available evidence. Similar findings have been reported in studies showing that statistical reasoning develops when learners engage in conceptual interpretations of uncertainty and inferential evidence (Budgett & Pfannkuch, 2018); (Chance & delMas, 2022); (Wild & Pfannkuch, 2023).

By Mission 3, the dimensions of evaluation and self-regulation became more prominent as students considered data variability and revised decisions based on the overall strength of available evidence. Students increasingly revisited earlier interpretations and reflected on the limitations of their conclusions before making final decisions. These findings support the view that critical thinking in statistical decision making involves monitoring, evaluating, and revising judgments in response to uncertainty (Chance & delMas, 2022; Zieffler & Garfield, 2020; delMas & Chance, 2021; Mawaddah et al., 2024).

The emergence of evaluation and self-regulation as the most prominent dimensions suggests that students gradually shifted from using statistics as a computational tool toward viewing statistical information as evidence for judgment and decision making. From a mindtools perspective, this development can be understood as the result of sustained interactions among learners, statistical representations, and progressively complex decision-making tasks. By enabling students to explore alternative interpretations, compare multiple indicators, and reconsider conclusions in light of new evidence, the mindtools-based environment functioned as a cognitive partner that supported reflective judgment and evidence-based decision making. Consequently, the development of critical thinking

observed in this study reflects not only increasing familiarity with statistical concepts but also the emergence of more sophisticated evaluative and self-regulatory practices.

5.4 Conceptual Model of Critical Thinking Development Through Mindtools-Based Statistical Decision Making

The findings of this study suggest that the development of critical thinking within a mindtools-based learning environment can be understood as a dynamic process involving interactions among task complexity, statistical representations, evidence evaluation, and reflective decision making. Rather than emerging directly from exposure to statistical content, critical thinking developed through repeated engagement with increasingly complex decision-making situations that required students to interpret data, evaluate evidence, and reconsider conclusions. Figure 5 presents the conceptual model developed from the findings of this study, illustrating how progressively designed learning missions and interactions with statistical representations support the development of students' critical thinking.

The conceptual model proposes that progressive mission complexity serves as the initial catalyst for cognitive engagement. As students encounter increasingly ambiguous and uncertain data, they are required to interact more deeply with statistical representations, including mean values, confidence intervals, and variability measures. These interactions encourage learners to move beyond procedural interpretation toward critical evaluation of evidence and consideration of alternative explanations. Through this process, statistical information becomes a resource for judgment rather than merely a computational outcome.

From a mindtools perspective, the learning environment functions as a cognitive mediator that supports exploration, comparison, and reflection. The model suggests that critical thinking develops when students repeatedly evaluate evidence and revise decisions in response to uncertainty. Consequently, the emergence of higher-order dimensions such as evaluation and self-regulation can be viewed as the outcome of sustained interactions among learners, statistical representations, and progressively challenging decision-making tasks. This model extends previous discussions of mindtools by illustrating a potential mechanism through which technology-mediated decision-making activities may foster the development of critical thinking in statistics education.

Conclusion and Implications

This study demonstrates that a spreadsheet-based learning game designed as a mindtools-based learning environment can support the development of students’ critical thinking in data-driven statistical decision making. The significant improvement in critical thinking scores suggests that engaging students in activities involving data interpretation, evidence evaluation, and decision justification can foster higher-order thinking skills in statistics learning. Beyond improvements in learning outcomes, the findings reveal that students’ thinking processes evolved from relying on single statistical indicators toward more reflective evaluation of evidence and decision revision in situations characterized by statistical uncertainty.

The findings further indicate that the development of critical thinking was not uniform across dimensions. While *interpretation* and *analysis* were most evident during the initial stages of interaction with statistical data, *evaluation* and *self-regulation* emerged more prominently as students encountered increasingly ambiguous decision-making situations. These results suggest that mindtools-based learning environments can support not only procedural understanding of statistical concepts but also the development of evaluative and reflective thinking required for evidence-based decision making.

From a pedagogical perspective, the study highlights the importance of designing statistics learning activities that engage students in authentic decision-making tasks involving uncertainty and competing evidence. Rather than emphasizing statistical procedures alone, learning environments should provide opportunities for students to evaluate evidence, reflect on alternative interpretations, and revise decisions based on available data. Such experiences may contribute to the development of critical thinking that is both contextually meaningful and applicable to real-world data-driven decision making.

Limitations and Future Research

Several limitations should be considered when interpreting the findings of this study. First, the investigation focused on students' thinking processes within three progressively designed learning missions. Although this design enabled the identification of developmental changes during data-driven statistical decision making, it did not capture how such developments might be sustained over longer periods of learning. Future research could examine the evolution of critical thinking and decision-making processes across multiple instructional cycles or extended learning contexts.

Second, the qualitative analysis relied primarily on students' written justifications, learning artifacts, reflective responses, and observational data collected during interactions with the mindtools-based learning environment. While these sources provided valuable evidence of observable thinking processes, they may not fully reveal the internal cognitive mechanisms underlying students' decisions. Future studies may benefit from incorporating complementary methods, such as think-aloud protocols or interviews, to gain deeper insights into how students evaluate evidence, regulate their thinking, and revise decisions during statistical problem solving.

Declarations

Funding

The authors received no specific funding for this research.

Conflict of Interest

The authors declare that they have no competing interests.

Ethical Approval

This study was reviewed by the Research Ethics Committee of Universitas Negeri Malang. The committee confirmed that the study complied with ethical principles for educational research involving adult participants (Reference No. 25.6.30/UN32.14/PB/2026).

Informed Consent

Informed consent was obtained from all participants prior to their participation in the study.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence

The authors used ChatGPT (OpenAI) to assist with language editing, translation, and manuscript refinement. All intellectual contributions, research design, data analysis, interpretation of findings, and final editorial decisions were made by the authors, who take full responsibility for the content of this manuscript.

Author Contribution

BS: conceived the study, designed the research, developed the spreadsheet-based learning environment, collected and analyzed the data, and drafted the original manuscript. CS: supervised the research, contributed to the conceptualization of the study, validated the research design and interpretation of the findings, and served as the corresponding author. LA, RR, S, TL, SF, AQ, and MH: contributed to the methodology, critically reviewed the manuscript, and provided important intellectual input for improving the study. All authors read, revised, and approved the final version of the manuscript.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

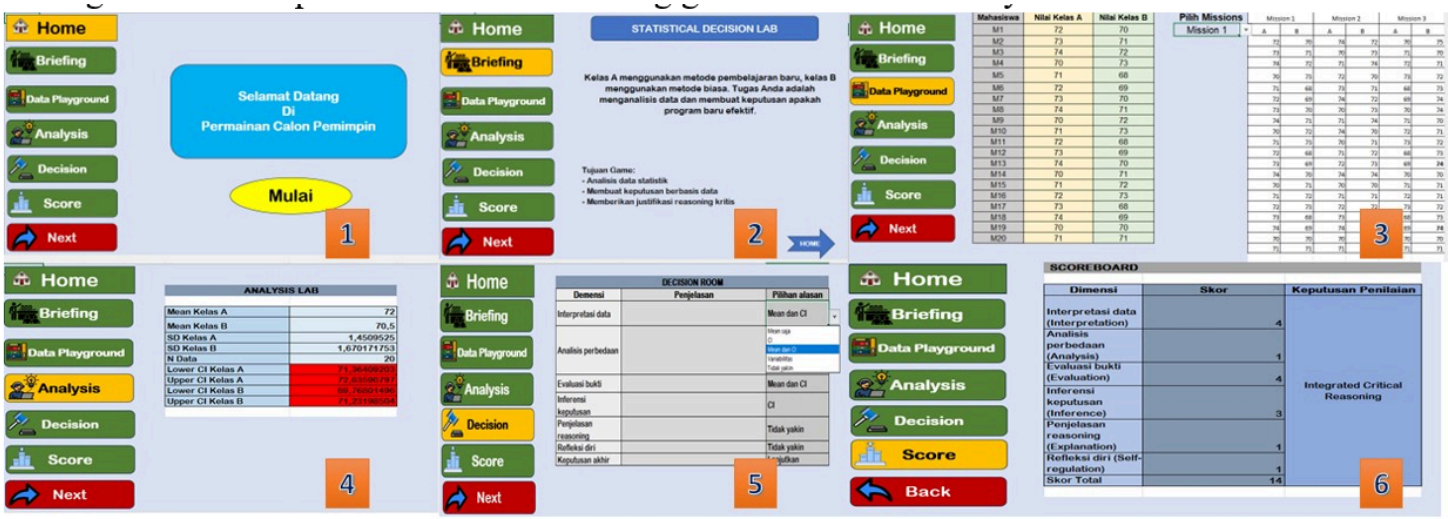
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Figures

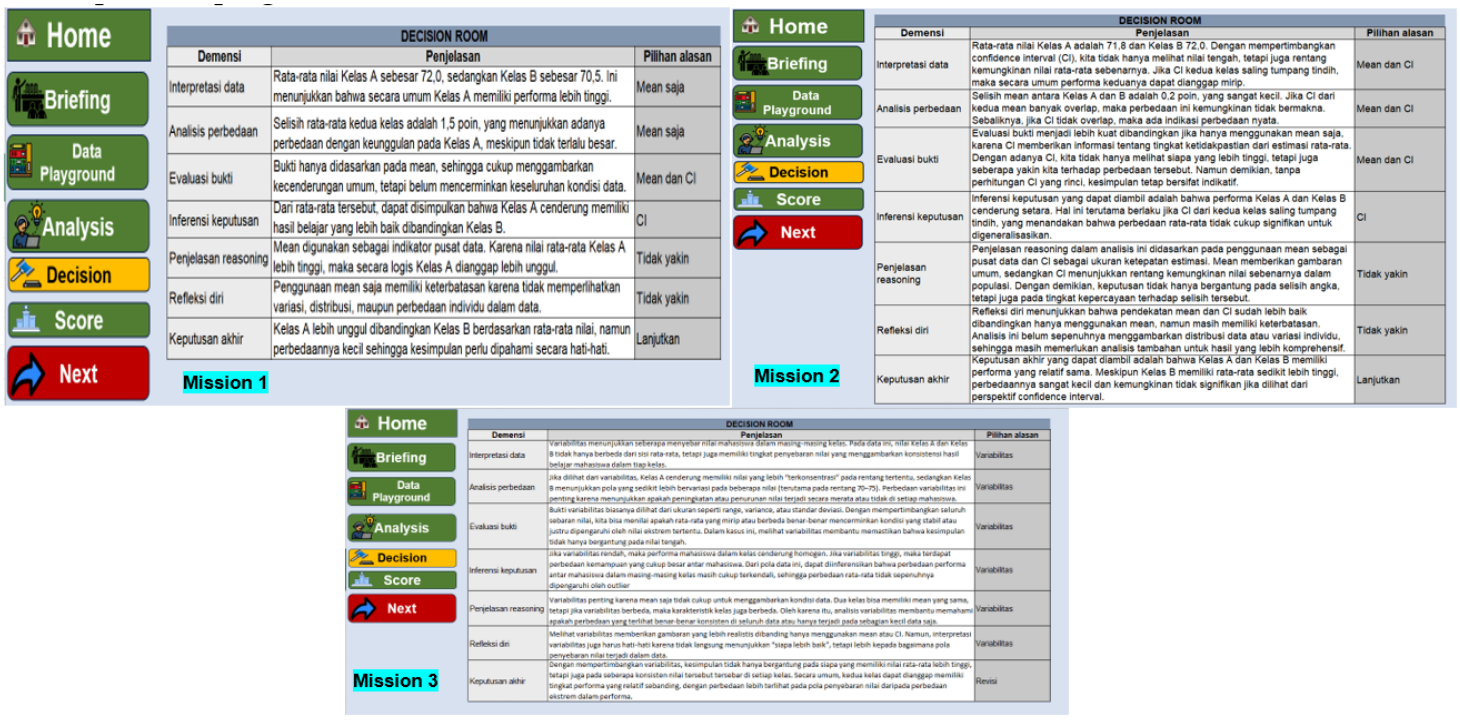


Panel descriptions:

(1) **Home Page** – Main menu of the learning game.
(2) **Briefing Page** – Introduction to the decision-making scenario and mission objectives.
(3) **Data Playground** – Interactive workspace for exploring statistical data.
(4) **Analysis Page** – Statistical analysis and evidence examination.
(5) **Decision Room** – Decision justification and reflection based on statistical evidence.
(6) **Scoreboard** – Feedback on performance across critical thinking dimensions.

Figure 1

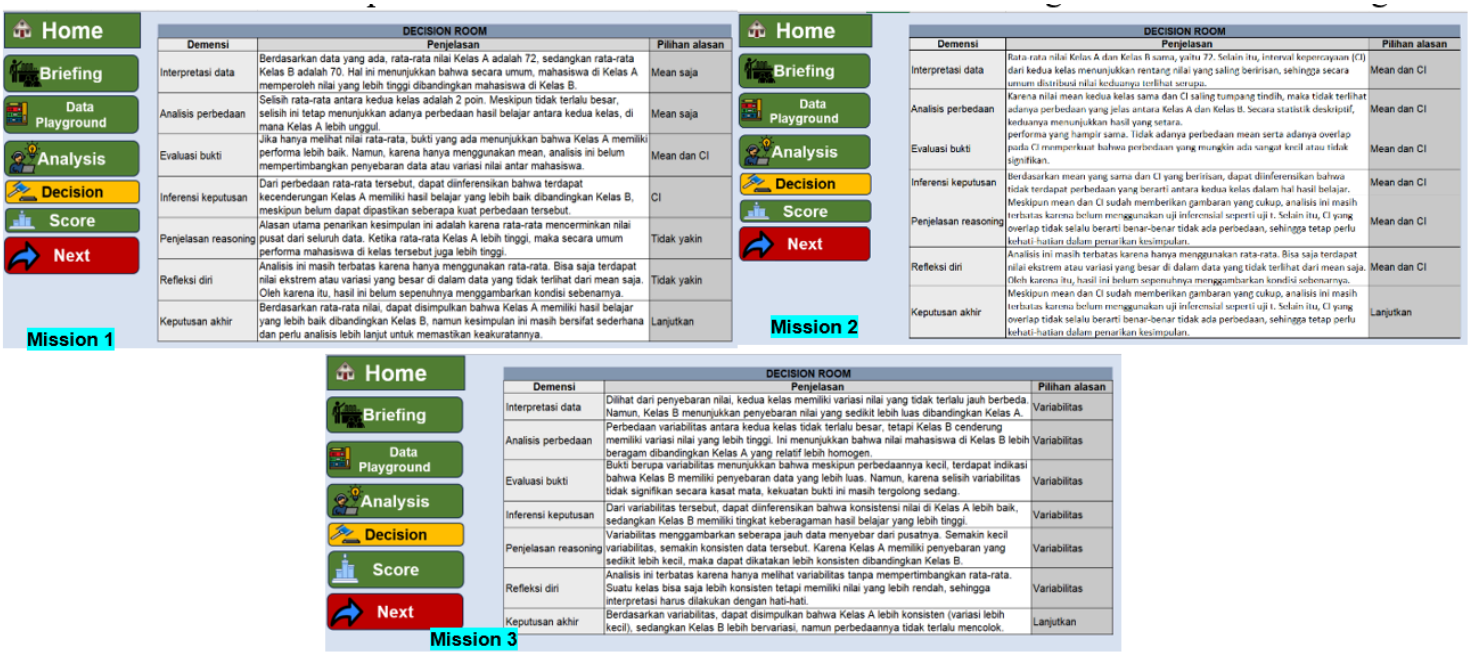
Interface and Learning Flow of the Spreadsheet-Based Learning Game



The original student responses are presented in Indonesian to preserve the authenticity of the learning artifacts. Their interpretation is provided in the accompanying text.

Figure 2

Development of Participant S1's Thinking Processes Across the Three Learning Missions



The original student responses were written in Indonesian and are presented as authentic learning artifacts. Interpretations of the responses are provided in the accompanying text.

Figure 3

Development of Participant S3's Thinking Processes Across Three Learning Missions

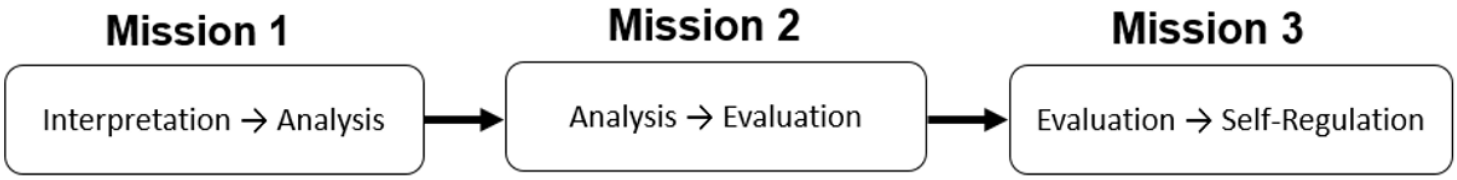


Figure 4

Development of Critical Thinking Dimensions Across Learning Missions

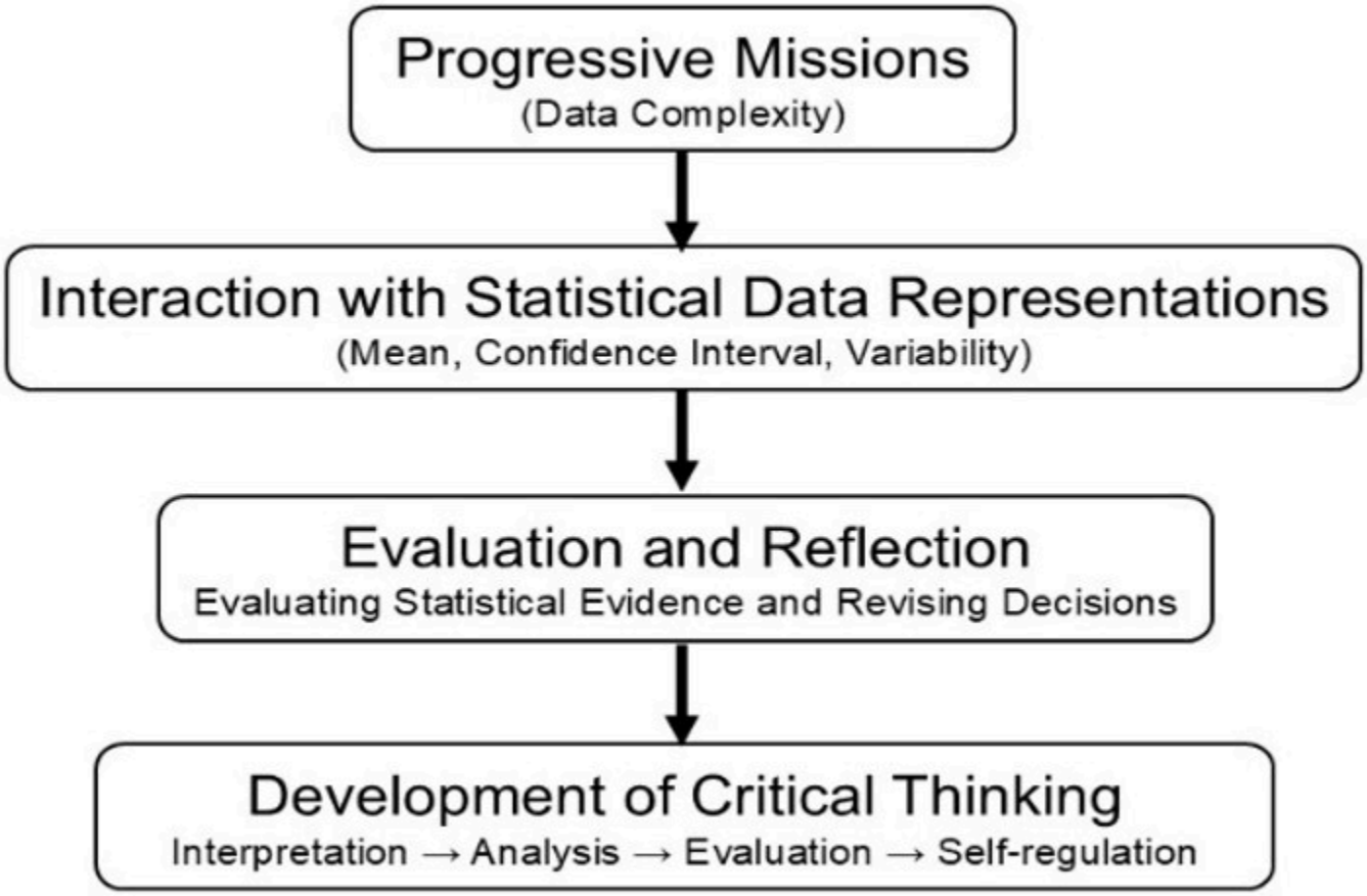


Figure 5

Conceptual Model of Critical Thinking Development Through Mindtools-Based Statistical Decision Making