Moderating Effects of Cognitive Load and Learning Engagement on Self-Regulated Learning Motivation and Academic Achievement

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The Asian Conference on Education 2024
Official Conference Proceedings

Abstract

This study aims to explore the moderating effects of increased cognitive load and learning participation on the relationship between autonomous learning motivation and academic achievement. The research subjects were seventh-grade students from a junior high school in New Taipei City, undergoing a six-week teaching intervention. The participants received a teaching intervention that incorporated increased cognitive load before and during classes. Data were collected using the Autonomous Learning Motivation Scale, Cognitive Load Scale, Learning Participation Scale, and Academic Achievement Test, and analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The results showed that: (1) autonomous learning motivation significantly positively predicted academic achievement; (2) increased cognitive load had a significant positive moderating effect on the relationship between autonomous learning motivation and academic achievement; (3) learning participation had a significant positive moderating effect on the relationship between autonomous learning motivation and academic achievement. These findings highlight the importance of increased cognitive load and learning participation. It is suggested that teachers should focus on providing learning scaffolds, guiding students to engage in higher-level cognitive processing, and creating an interactive and engaging learning environment to enhance students' autonomous learning motivation and academic achievement.

Keywords: Autonomous Learning Motivation, Germane Cognitive Load, Learning Participation, Academic Achievement

Introduction

With the advancement of technology and developments in the field of education, digital learning environments have become an important medium for teaching. How to enhance students' learning motivation in digital learning environments and thus promote academic achievement is a significant issue in current educational research. Previous studies have shown that learning motivation is a key factor affecting academic achievement (Brown, 2022; Lazzari, 2023; Nugraheni et al., 2022). At the same time, cognitive load and learning participation also play important moderating roles in the learning process (Kalyuga, 2011; Kirschner et al., 2009; Paas & Van Merriënboer, 1994; Renkl & Atkinson, 2003; Van Merriënboer et al., 2006). However, empirical research on the relationship between learning motivation, cognitive load, learning participation, and academic achievement, especially in digital learning environments, is still limited.

Although existing studies have explored the impact of learning motivation on academic achievement (Cerasoli et al., 2014; Kriegbaum et al., 2018; Lazowski & Hulleman, 2016; Mayer, 2014; Ryan & Deci, 2020), the role of cognitive load and learning participation as moderating variables in digital learning environments has not received sufficient attention and research. Therefore, this study attempts to build on previous research to explore the relationships between autonomous learning motivation, increased cognitive load, learning participation, and academic achievement, with the aim of expanding the relevant research field and providing new perspectives and bases for optimizing digital learning environments.

Learning motivation refers to an individual's psychological tendency to become interested in learning activities and willing to invest time and effort, which is an important factor driving learning behavior and influencing learning outcomes (Ryan & Deci, 2020). Self-Determination Theory (SDT) divides motivation into intrinsic motivation and extrinsic motivation, emphasizing that individuals will generate high-quality intrinsic motivation when their basic psychological needs for autonomy, competence, and relatedness are satisfied, thereby enhancing learning engagement and performance (Ryan & Deci, 2017). Numerous empirical studies support the view of Self-Determination Theory, finding a significant positive relationship between intrinsic motivation and academic achievement (Cerasoli et al., 2014; Lazowski & Hulleman, 2016; Taylor et al., 2014). For example, a meta-analysis by Cerasoli and colleagues (2014) found that the average correlation coefficient between intrinsic motivation and academic performance was 0.27, while the correlation coefficient for extrinsic motivation was only 0.14. Additionally, intrinsic motivation has been found to predict variables such as learning satisfaction, persistence, and creativity (Howard et al., 2021; Jeno et al., 2019).

However, the rich information and complex interactions in digital learning environments may place higher demands on students' cognitive processing, leading to additional cognitive load (Kalyuga, 2011; Mayer, 2014). Cognitive Load Theory (CLT) posits that learners' working memory is affected by intrinsic cognitive load, extraneous cognitive load, and germane cognitive load (Sweller, 2010). Intrinsic cognitive load stems from the complexity of the learning material itself, extraneous cognitive load arises from flaws in instructional design, and germane cognitive load is associated with the mental effort learners invest in the learning process (Leppink et al., 2013). While an appropriate cognitive load can facilitate learning, excessive cognitive load can interfere with learning (Paas & Van Merriënboer, 2020). For instance, Chen and Wu (2012) found that students' extraneous cognitive load increased significantly when faced with complex multimedia learning materials, resulting in decreased learning performance. Similarly, Lin and Chen (2017) found that when the intrinsic complexity of learning tasks exceeded students' ability levels, it triggered a higher intrinsic cognitive load, thereby affecting learning outcomes.

Given this, it is hoped that the teaching design context in this study can provide appropriate germane cognitive load in line with the current textbook structure to enhance learning outcomes.

Learning participation refers to the degree of students' engagement in the learning process, including behavioral engagement, emotional engagement, cognitive engagement, and agentic engagement (Fredricks et al., 2004). Behavioral engagement refers to students' participation and effort in learning activities, emotional engagement refers to students' interest and value recognition in learning, and cognitive engagement refers to students' thinking and strategy use regarding learning content (Reeve, 2013). Higher levels of learning participation are considered important mediating variables between learning motivation and academic achievement (Jang et al., 2016; Reeve & Lee, 2014). For example, Jang and colleagues (2016) found that teacher support for students' autonomy significantly enhanced students' learning participation, thereby promoting academic performance. Similarly, Reeve and Lee (2014) found that students' learning participation at the beginning of the semester could predict academic performance at the end of the semester, and improved academic performance further reinforced students' learning participation, creating a positive cycle. In this teaching design context, appropriate guiding activities are introduced in response to different levels of participation, aiming to enhance learning participation before and during the course, thus improving academic achievement.

Literature Review

Autonomous learning motivation, increased cognitive load, and learning participation are three important research themes in the field of educational psychology and form the theoretical basis for this study. These three themes reveal key factors influencing students' learning processes and outcomes from motivational, cognitive, and behavioral perspectives. This paper will systematically review the theoretical foundations, current research status, and future prospects of these three themes to provide an integrated perspective for understanding the complex mechanisms of student learning.

Autonomous Learning Motivation

Autonomous learning motivation refers to the drive for students to voluntarily and continuously invest time and effort in the learning process (Ryan & Deci, 2017). Self-Determination Theory (SDT) is an important theoretical framework for explaining autonomous learning motivation (Deci & Ryan, 1985; Ryan & Deci, 2000). The theory posits that humans have three basic psychological needs: autonomy, competence, and relatedness. When the learning environment satisfies these needs, students exhibit higher autonomous learning motivation (Ryan & Deci, 2020).

Numerous empirical studies support the hypotheses of the Self-Determination Theory. For example, Jang and colleagues (2016) used experience sampling to examine high school student's classroom learning motivation and found that teachers' autonomy-supportive behaviors significantly predicted students' autonomous learning motivation, influencing their classroom engagement and learning performance. Similarly, a meta-analysis by Patall and colleagues (2022) found that teachers' provision of choices, rationales, and empathy - autonomy-supportive behaviors - was significantly positively correlated with students' autonomous learning motivation (r=.31). However, effectively enhancing students' autonomous learning motivation in educational practice remains challenging. On one hand, students of different ages and cultural backgrounds may have different needs for autonomy support (Chirkov, 2009; Reeve et al., 2020). For example, Reeve and colleagues (2020) found that compared to Western countries, students in Asian countries are more inclined to accept teachers' guidance and control. On the other hand, while supporting students' autonomy, teachers also need to provide appropriate structure and guidance to help students construct knowledge and skills (Jang et al., 2010; Sierens et al., 2009). For example, Sierens and colleagues (2009) found that the interaction effect between teachers' autonomy support and structure was most beneficial for enhancing students' learning motivation when the two were moderately combined.

Future research can further explore how teachers implement autonomy support in different subjects and teaching stages and how to integrate autonomy support with other teaching strategies (such as competence support and relatedness support) to create the optimal learning environment (Jang et al., 2016; Stroet et al., 2013). Additionally, exploring the relationship between students' personal characteristics (such as achievement goal orientation and attribution style) and autonomous learning motivation can help implement personalized teaching interventions (Dompnier et al., 2015; Kusurkar et al., 2013).

In summary, autonomous learning motivation, as a high-quality type of motivation, can promote the depth and breadth of learning by guiding students to engage more in cognitive processes directly related to learning content. In digital learning environments, it is worth exploring how to meet students' needs for autonomy, competence, and relatedness through task design and instructional interactions, thereby enhancing their autonomous learning motivation. Accordingly, this study proposes the following hypothesis:

Hypothesis 1: Autonomous learning motivation positively predicts academic achievement.

Germane Cognitive Load

Increased cognitive load refers to the cognitive processing that learners engage in to deeply understand learning materials, which has a positive impact on learning (Sweller et al., 2019). According to Cognitive Load Theory, there are three types of cognitive load in the learning process: intrinsic cognitive load, extraneous cognitive load, and germane cognitive load (Sweller, 2010). Intrinsic cognitive load arises from the complexity of the learning material itself, extraneous cognitive load comes from unnecessary instructional design, and germane cognitive load stems from learners' active cognitive processing for knowledge construction (Sweller et al., 2019).

CLT emphasizes that instructional design should reduce extraneous cognitive load while promoting germane cognitive load to optimize learning outcomes (Kalyuga, 2011). For instance, van Merriënboer and Sweller (2005) proposed four instructional design principles to reduce extraneous load and increase germane load: the goal-free effect, worked example effect, completion problem effect, and inductive problem-solving effect. The effectiveness of these principles has been supported by numerous empirical studies (Renkl, 2014; van Gog & Rummel, 2010).

However, whether students can benefit from germane cognitive load depends on their prior knowledge level. According to the expertise reversal effect, instructional designs that are effective for novices may have negative impacts on more advanced learners (Kalyuga, 2007). For instance, for students who already have relevant knowledge, too much guidance and examples may interfere with their knowledge integration and deep processing (Kalyuga & Renkl, 2010). Therefore, teachers need to adjust instructional design based on students' expertise levels to provide optimal cognitive load for students of different levels (Kalyuga & Singh, 2016).

Future research can further explore the specific forms and measurement methods of germane cognitive load and its application strategies in different subjects and learning stages (de Jong, 2010; Leppink et al., 2014). Additionally, researchers are also calling for attention to learners' subjective experiences of cognitive load and the relationship between subjective and objective measures (Klepsch & Seufert, 2020; Seufert, 2020). Integrating subjective and objective measures can help comprehensively understand the mechanisms of cognitive load and provide more precise guidance for instructional practice.

To reduce ineffective load and increase the effective load, the principles for designing digital learning materials include the goal-free effect, worked example effect, completion effect, split-attention effect, redundancy effect, expertise reversal effect, and transient information effect (International Cognitive Load Theory Workshop).

According to Cognitive Load Theory, germane cognitive load can be further divided into elaborative load, example-based load, variability load, explanatory load, goal-oriented load, and interactive load (Kalyuga, 2011). These types of germane load should be selected and designed based on learning content and goals to optimize learning outcomes while balancing intrinsic, extraneous, and germane cognitive load to avoid overall cognitive overload (Van Merriënboer & Sweller, 2005).

Based on the aforementioned literature, this study proposes the following hypothesis:

Hypothesis 2: Germane cognitive load positively moderates the relationship between autonomous learning motivation and academic achievement. That is, when students invest more germane cognitive load, the positive correlation between autonomous learning motivation and academic achievement is stronger.

Learning Participation

Learning participation refers to the degree of students' engagement in the learning process, including behavioral, emotional, cognitive, and agentic dimensions (Fredricks et al., 2004). Behavioral participation refers to students' effort and involvement in learning activities, emotional participation refers to students' interest and value recognition in learning, cognitive participation refers to students' thinking and strategy use regarding learning content, and agentic participation refers to students' proactive efforts to enhance and improve the learning process (Reeve, 2013). Higher levels of learning participation are considered important mediating variables between learning motivation and academic achievement (Jang et al., 2016; Reeve & Lee, 2014).

For example, Chiu (2021) found that providing timely encouragement and support in flipped classrooms significantly enhanced students' learning motivation and self-efficacy. Pan and colleagues (2019) also showed that giving students successful experiences, such as guiding them to complete pre-learning tasks, can promote positive emotional experiences.

Erbil (2020) pointed out that using interactive teaching strategies like group discussions and role-playing in flipped classrooms can significantly increase students' classroom participation. Turan and Goktas (2018) found that guiding students to think actively and express their views before class can promote their active participation in classroom discussions.

Steen-Utheim and Foldnes (2018) showed that encouraging students to ask questions, think deeply, and reflect in flipped classrooms can enhance their critical thinking and metacognitive abilities. Låg and Sæle (2019) found that guiding students to summarize principles and connect knowledge can lead to more meaningful learning.

Hew and colleagues (2020) pointed out that giving students opportunities to evaluate and provide feedback in flipped classrooms can increase their sense of ownership and participation. Ng (2018) emphasized that establishing democratic and equal teacher-student relationships and creating a fair learning environment can promote students' active participation in the learning process.

Further exploration shows that factors influencing students' learning participation include personal and environmental aspects. At the personal level, students' self-efficacy, goal orientation, and attribution style significantly affect learning participation (Ames, 1992; Bandura, 1997; Dweck & Leggett, 1988). For example, Schunk and DiBenedetto (2016) showed that when students believe they can complete learning tasks and attribute learning outcomes to their efforts, they display higher learning engagement. At the environmental level, teachers' instructional practices, peer relationships, and school climate significantly influence students' learning participation (Furrer & Skinner, 2003; Jang et al., 2010; Wang & Eccles, 2013). For instance, Reeve (2006) found that teachers who provide choices and support autonomy significantly increase students' classroom engagement. Recent theories of learning participation further expand its content, proposing the concept of agentic engagement, which emphasizes students' active creation and optimization of their learning environment to meet their learning needs (Reeve, 2013; Reeve & Tseng, 2011). For example, Matos and colleagues (2018) found that when students actively seek teachers' help and feedback and express their ideas and suggestions, their learning experiences are more positive and learning outcomes more ideal.

Although learning participation is crucial for students' development, enhancing it remains challenging. In the digital age, students face more distractions and temptations, making it important for educators to focus on maintaining focus and engagement in technology-rich environments (Bergdahl et al., 2020). Additionally, the measurement and intervention of learning participation face methodological limitations, requiring diversified research designs, such as combining self-reports, behavioral observations, and physiological indicators to deeply understand the mechanisms and influencing factors of participation (Azevedo, 2015; Sinatra et al., 2015).

In summary, recent studies further support the application of learning participation theories in flipped classrooms and provide more empirical evidence. This study will incorporate these recent research findings in designing and practicing to enhance students' participation from multiple dimensions for better teaching outcomes.

Based on the above, learning participation can be seen as an important process through which learning motivation affects academic achievement. However, there is still insufficient empirical support for the moderating role of learning participation in this relationship. Therefore, this study proposes the following hypothesis:

Hypothesis 3: Learning participation positively moderates the relationship between autonomous learning motivation and academic achievement. That is, when students exhibit higher learning participation, the positive correlation between autonomous learning motivation and academic achievement is stronger.

Research Methodology

Research Subjects

The study targets seventh-grade students from a junior high school in New Taipei City, using purposive sampling to select two classes totaling 60 students. The students received instructional designs incorporating scaffolds and increased cognitive load. The pre-test scores of the two classes showed no significant difference based on their previous semester's science grades.

Research Instruments

(a) Autonomous Learning Motivation Scale: The "Learning Motivation Scale" developed by Ryan and Deci (2000) includes subscales for intrinsic motivation, identified regulation, external regulation, and motivation, with a total of 9 items. This study uses only the intrinsic motivation subscale, with a Likert 5-point scale (1 = strongly disagree, 5 = strongly agree). Higher scores indicate stronger autonomous learning motivation. The Cronbach's α value for internal consistency in this study's sample is 0.89.

(b) Cognitive Load Scale: The "Multidimensional Cognitive Load Scale" by Leppink and colleagues (2013) was adapted to create the "Germane Cognitive Load Scale," which includes four dimensions: elaborative load, example-based load, variability load, and explanatory load, with a total of 12 items. Higher scores indicate a higher perceived germane cognitive load. The Cronbach's α value for internal consistency in this study's sample is 0.90.

(c) Learning Participation Scale: The "Four-Dimensional Learning Participation Scale" by Reeve and Tseng (2011) includes behavioral, emotional, cognitive, and agentic participation, with a total of 24 items. Higher scores indicate higher levels of learning participation. The Cronbach's α value for internal consistency in this study's sample is 0.87.

Instructional Design

The experimental group received a four-week instructional intervention. The content was based on the seventh-grade science unit "Biological Evolution."

The instructional goals include exploring the relationship between fossils and evolution, understanding the types and formation of fossils, analyzing fossil evidence for evolution, and understanding core concepts of biological evolution theories.

The instructional design mainly follows the principles of Cognitive Load Theory and scaffolding theory. Before the class, teachers provided conceptual scaffolds such as reading prompts and key points to guide students in previewing key concepts. During the class, procedural scaffolds such as demonstrating evolutionary reasoning and providing thinking frameworks were used to help students solve problems. Teachers also incorporated tasks such as variation exercises and reflective questions to induce students' engagement in elaborative and higher-order cognitive processing related to learning content, aiming to construct more comprehensive knowledge structures.

Data Analysis

This study used SmartPLS 3 for Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis. PLS-SEM is preferred over Covariance-Based Structural Equation Modeling (CB-SEM) for its higher statistical power when dealing with small samples and non-normal data, and it is suitable for both theory validation and development (Hair et al., 2019).

Analysis steps include evaluating the reliability and validity of the measurement model, evaluating the explanatory power of the structural model, and testing the significance of path coefficients and moderating effects. The reliability of latent variables is assessed using composite reliability (CR), convergent validity using average variance extracted (AVE), and discriminant validity using the Fornell-Larcker criterion. The explanatory power of the structural model is evaluated using R^2, and the effect size of predictor variables using f^2. Bootstrapping is used to test the significance of path coefficients, and the two-stage approach is used to analyze moderating effects.

Results

1. ***Measurement Model Analysis***

Table 1 shows that the composite reliability of the latent variables ranges from 0.89 to 0.92, exceeding the threshold of 0.70 (Hair et al., 2019). The AVE ranges from 0.65 to 0.72, exceeding the standard of 0.50, indicating good convergent validity. Additionally, the square root of the AVE of each variable is greater than its correlations with other variables, meeting the Fornell-Larcker criterion and supporting discriminant validity. Overall, the measurement model is reliable and valid.

2. ***Structural Model Analysis***

The R^2 for academic achievement as the dependent variable is 0.45, indicating moderate explanatory power of the model. Regarding the research hypotheses, autonomous learning motivation has a significant positive impact on academic achievement (β=0.32, t=3.81, $p < 0.001$), with a medium effect size (f^2=0.15), supporting Hypothesis 1.

Table 1: Summary of Measurement Model Analysis

Latent Variables	CR	AVE	Autonomous Learning Motivation	Cognitive Load Increase	Learning Participation	Learning Achievement
Autonomous Learning Motivation	0.92	0.72	(.85)	-	-	-
Cognitive Load Increase	0.91	0.68	0.56	(.82)	-	-
Learning Participation	0.90	0.65	0.61	0.53	(.81)	-
Learning Achievement	0.89	0.67	0.63	0.58	0.67	(.82)

Note. The diagonal elements represent the square root of AVE; the off-diagonal elements represent correlations among variables.

As shown in Figures 1 and Figures 2, the interaction terms between germane cognitive load and autonomous motivation significantly affect academic achievement (moderating effect=6.872>1.96), supporting Hypothesis 2. This indicates that germane cognitive load can enhance the moderating effect of autonomous motivation on achievement.

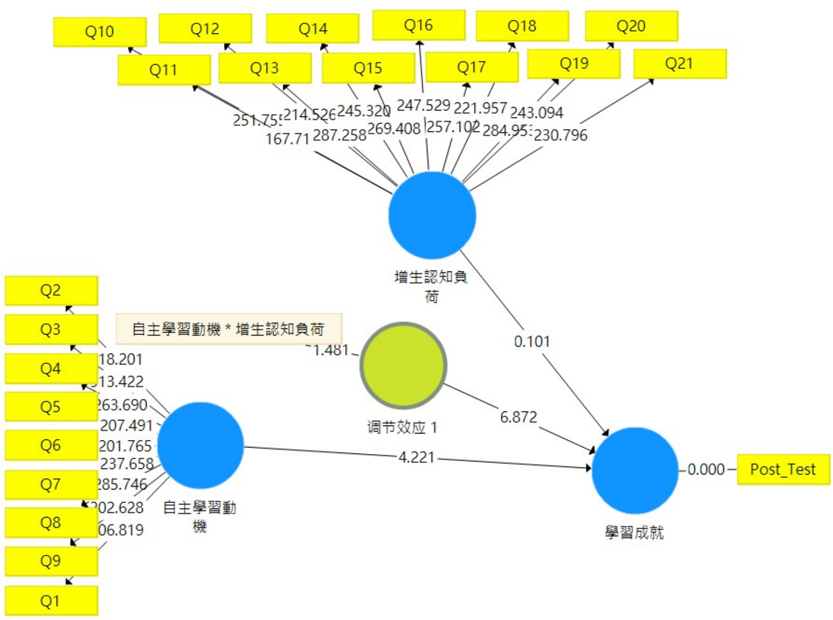

Figure 1: PLS-SEM Results of Germane Cognitive Load Regulation Analysis

Similarly, the interaction terms between learning participation and autonomous motivation significantly affect academic achievement (moderating effect=3.703>1.96), supporting Hypothesis 3. This indicates that learning participation can strengthen the positive impact of autonomous motivation on achievement.

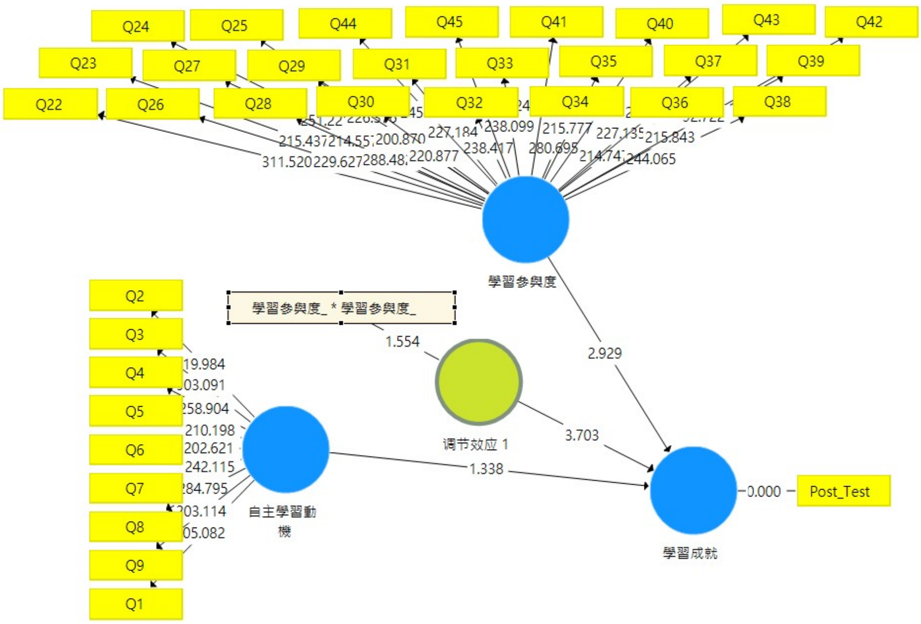

Figure 2: PLS-SEM Learning Engagement Moderates Analysis Results

Discussion

1. *Impact of Autonomous Learning Motivation on Academic Achievement*

This study found that autonomous learning motivation significantly positively predicts academic achievement, consistent with previous research (Jeno et al., 2019; Lin, 2021). This suggests that when students engage in learning based on intrinsic interest and value recognition, they are more likely to adopt deeper cognitive strategies and invest more effort, resulting in better academic performance. This finding supports the view of Self-Determination Theory, which posits that autonomous learning motivation benefits cognitive development and academic progress.

2. *Moderating Effect of Germane Cognitive Load*

This study further examined the role of germane cognitive load in the relationship between autonomous learning motivation and achievement. The results show that germane cognitive load moderates this relationship, with higher levels of germane cognitive load enhancing the positive impact of autonomous motivation on achievement. This finding echoes the main assertions of Cognitive Load Theory, which emphasizes that instructional design should reduce extraneous load, manage intrinsic load, and promote germane load to guide students into higher-order cognitive processing and genuinely enhance learning (Kalyuga, 2011; Sweller et al., 2019).

It is important to note that germane cognitive load is not about quantitative accumulation but qualitative improvement. As Seufert (2018) noted, not all forms of cognitive investment bring positive effects; only cognitive efforts closely related to learning goals and capable of inducing conceptual reorganization can be considered a true germane load. Therefore, teachers should design tasks that not only control the total load but also focus on inducing higher-order cognitive processes like reflection, reasoning, and knowledge integration.

3. *Moderating Effect of Learning Participation*

This study also found that higher levels of learning participation strengthen the positive correlation between autonomous learning motivation and academic achievement. In other words, students with high autonomous motivation who exhibit active learning behaviors and invest more cognitive and emotional resources are more likely to achieve positive learning outcomes. This finding partially supports Reeve's (2012) view that participation should encompass both quantitative and qualitative aspects, with behavioral involvement alone being insufficient; emotional recognition and cognitive strategies must also be integrated to truly enhance learning.

For educational practice, teachers should provide engaging task contexts that meet students' needs for autonomy, competence, and relatedness, thereby enhancing their autonomous learning motivation. At the same time, creating supportive teacher-student interactions and peer cooperation atmospheres, encouraging idea expression, and providing constructive feedback can guide students to achieve higher-quality engagement across behavioral, emotional, and cognitive dimensions, thereby enhancing the impact of learning motivation on academic achievement.

4. *Contributions*

This study makes several important contributions to the field of educational psychology. First, it empirically validates the moderating roles of germane cognitive load and learning participation in the relationship between autonomous learning motivation and academic achievement, extending the existing research on these constructs. The findings highlight the importance of considering cognitive and behavioral factors alongside motivational ones in optimizing learning outcomes.

Second, the study presents a detailed instructional design model incorporating scaffolding and germane cognitive load principles in science education. This model provides a practical framework for teachers to create learning environments that support students' autonomy, guide them into higher-order thinking, and foster active participation. The effectiveness of this model, as demonstrated by the study's results, offers valuable insights for instructional practice.

Third, by focusing on junior high school students and the subject of science, this study helps fill a gap in the literature, as much of the prior research on cognitive load and learning participation has been conducted with older students or in other domains. The findings suggest that these principles are applicable and beneficial across a wider range of educational contexts than previously established.

Finally, the study's use of PLS-SEM analysis represents a methodological contribution, demonstrating the value of this approach for handling complex relationships between latent variables in educational research. The combination of theoretical grounding and rigorous empirical testing employed in this study serves as a model for future investigations in this area.

Conclusion and Recommendations

This study investigated the moderating roles of germane cognitive load and learning participation in the relationship between autonomous learning motivation and academic achievement among junior high school students. The findings support that autonomous learning motivation significantly positively predicts academic achievement, and that higher levels of germane cognitive load and learning participation enhance this effect.

These results reinforce the empirical foundations of Cognitive Load Theory and Self-Determination Theory, highlighting that instructional design should balance cognitive load, motivational processes, and engagement quality. Through a four-week teaching intervention, this study presented a teaching model incorporating scaffolding and germane cognitive load in science education.

By providing conceptual and procedural scaffolds, teachers guided students into inquiry contexts, focusing on core concepts and mastering key strategies. Simultaneously, through variation exercises and reflective tasks, teachers induced students to invest in more elaborative and integrative cognitive resources, creating potential development spaces for students.

This study's findings offer several insights for designing digital learning environments and fostering motivation in teaching. Firstly, teachers should carefully evaluate the cognitive load of digital materials, providing appropriate scaffolding to help students focus on key points and master essential strategies. Secondly, teachers should design task contexts that guide students into higher-order cognitive processing through analogy, reflection, and knowledge integration. Furthermore, teachers should create collaborative learning and peer feedback mechanisms to stimulate students' active participation in behavioral, emotional, and cognitive dimensions, fully enhancing the motivational impact on learning outcomes. Lastly, for students of different achievement levels, instructional design should provide necessary support while ensuring equal opportunities for high-standard learning, aiming to achieve the ideal of both equity and excellence in education.

Although this study has preliminarily validated the effectiveness of instructional designs incorporating germane load, there are still some limitations worth exploring in future research. Firstly, this study focused only on junior high school students and the field of science; future studies could expand to different age groups and subjects to examine the cross-context applicability of this model. Secondly, this study focused on students' cognitive and motivational performances, while social interactions and environmental contexts may also influence students' perceptions of load and learning engagement, which deserve further consideration. Moreover, as germane load is essentially a psychological investment state that is difficult to measure directly, future studies could use qualitative data such as interviews and think-aloud protocols to explore students' cognitive processes in different instructional activities in more detail. Lastly, this study adopted a quasi-experimental design, which can establish preliminary causal relationships between variables; however, the complexity of educational contexts makes it challenging to control for all confounding factors. Future studies could use longitudinal tracking designs to comprehensively explore the long-term interactions between instructional, individual, and contextual factors.

In summary, facing the rapid changes in learning modes in the digital age, guiding students to appropriately invest cognitive resources in rich information contexts, enhancing learning motivation and engagement, and ultimately optimizing learning outcomes are urgent issues for educators. This study integrates theories and empirical evidence to provide clues for instructional practice. Only by supporting students to exceed their current cognitive levels through appropriate guidance and engaging them in meaningful cognitive processing, while stimulating high-quality engagement in behavioral, emotional, and cognitive dimensions, can we truly realize the potential of every unique learner. The journey of teaching and learning begins with appropriate design, based on students' needs, and continuously improves in dynamic balance.

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