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Cognitive Reserve Depletion and Learning Autonomy Recovery in Generative Artificial Intelligence Dependent Educational Environments

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A R T I C L E I N F O

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A B S T R A C T

This study examines how generative Artificial Intelligence (AI) dependence relates to cognitive reserve depletion and learning autonomy among university students. Using a quasi-experimental design, the study involved 120 students from two universities in Padang, Indonesia, divided equally into intervention and control groups. Data were analyzed using linear regression and ANCOVA following a four-week learning autonomy recovery program. The statistical estimates showed a positive relationship between AI dependence and cognitive reserve depletion (B = 0.698, p < 0.001), while cognitive reserve depletion was negatively associated with learning autonomy (B = −0.482, p < 0.001). The intervention showed a positive adjusted effect (B = 0.334, p < 0.001), highlighting the importance of developing independent learning practices alongside AI use.

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INTRODUCTION

University students are increasingly incorporating generative artificial intelligence (AI) into their everyday academic activities, often turning to tools such as ChatGPT when preparing assignments, exploring unfamiliar concepts, or organizing their ideas. What once required prolonged reading, discussion, and independent reflection can now be completed with immediate technological assistance. This convenience offers meaningful opportunities for learning, particularly when students need additional explanations or guidance beyond classroom instruction. Yet, it also raises an educational concern: whether students continue to engage deeply with the intellectual processes involved in understanding and solving problems, or gradually become accustomed to receiving ready-made answers. Deng et al. (2025), in a systematic review and meta-analysis of 69 experimental studies, reported that ChatGPT could improve academic performance and certain aspects of higher-order thinking while reducing mental effort. Their findings suggest that the effectiveness of AI-supported education cannot be understood solely through improvements in academic outcomes, as the quality of students' cognitive engagement remains equally important. Understanding this relationship is essential for ensuring that generative AI supports students' intellectual development without weakening their ability to learn and think independently.

The growing dependence on generative AI has also introduced new challenges concerning students' cognitive engagement and their ability to regulate learning independently. When students repeatedly rely on AI to generate arguments, solve problems, or make academic decisions, they may have fewer opportunities to practice the mental processes that support reasoning, reflection, and intellectual confidence. This concern is closely related to cognitive offloading, through which individuals transfer certain cognitive activities to external tools to reduce the demands placed on their own mental resources. Although cognitive offloading can support efficiency, its consequences may become less beneficial when technological assistance substitutes for rather than supports meaningful intellectual engagement. Stern et al. (2020) emphasized that cognitive reserve represents the capacity to maintain cognitive functioning despite challenges, while recognizing that its conceptualization and measurement require careful theoretical distinction. Within the present educational discussion, cognitive reserve depletion refers to the proposed weakening of independently exercised cognitive resources and learning-related mental engagement, rather than a clinically established reduction in neurological reserve. This perspective is particularly relevant to higher education in Indonesia, including West Sumatra, where understanding students' relationship with generative AI is important for maintaining a balance between technological advancement and human intellectual development.

Existing studies have demonstrated that artificial intelligence can contribute positively to students' learning experiences, particularly when it is integrated into educational activities that encourage reflection and self-regulation. Guan et al. (2025), in a systematic review of 27 publications, found that educational chatbots primarily supported students in identifying learning resources, applying learning strategies, and monitoring their academic progress. However, the same review revealed that comparatively limited support was provided for establishing learning goals, developing independent learning plans, and reflecting on previous learning experiences. Similarly, Lan and Zhou (2025), through a systematic review of AI-supported self-regulated learning in higher education, highlighted the potential of intelligent learning technologies to strengthen learner autonomy when their implementation is aligned with students' educational needs. These findings suggest that the relationship between AI and learning autonomy is not inherently negative, as technological assistance may enhance independent learning when students remain actively involved in their academic decisions. Nevertheless, Abdallah et al. (2025) identified concerns about excessive reliance on ChatGPT, including its possible implications for independent learning, critical engagement, and students' broader educational development. The contrasting findings indicate that the educational consequences of generative AI depend not only on the technology itself but also on the extent to which students retain responsibility for their own thinking and learning processes.

Despite the growing literature on generative AI in education, several important questions remain insufficiently addressed, particularly regarding the relationship between technological dependence, cognitive engagement, and the recovery of learning autonomy. Previous studies have largely emphasized the educational benefits of AI, its influence on academic performance, and its capacity to support self-regulated learning, while comparatively less attention has been directed toward how students might regain intellectual independence after developing excessive reliance on AI-generated assistance. Deng et al. (2025) acknowledged limitations in existing experimental research, particularly the need for stronger evidence concerning learning outcomes that extend beyond immediate task performance. Meanwhile, Guan et al. (2025) and Lan and Zhou (2025) highlighted the importance of learning regulation but did not establish a comprehensive explanation of how cognitive dependence and the restoration of learning autonomy are connected. Another conceptual gap concerns the interpretation of cognitive reserve depletion within AI-dependent educational environments, as the concept of cognitive reserve originates from cognitive neuroscience and cannot automatically be equated with reduced learning effort or technological dependence (Stern et al., 2020). These limitations point to the need for a more carefully defined educational perspective that distinguishes the benefits of cognitive assistance from the potential weakening of independently practiced thinking. More importantly, the existing literature provides a foundation for investigating whether learning autonomy can be strengthened when students are encouraged to reassume an active role in reasoning, evaluating information, and making academic decisions.

Responding to these concerns, the present study aims to examine the relationship between generative AI dependence, cognitive reserve depletion, and learning autonomy in higher education. The study focuses on understanding whether greater reliance on AI-generated assistance is associated with indicators of reduced independent cognitive engagement and whether these indicators are related to students' capacity to manage their own learning. Beyond identifying these relationships, the study also seeks to explore the potential for learning autonomy recovery through educational practices that restore students' responsibility for intellectual decision-making. The central argument is that the educational challenge associated with generative AI should not be understood exclusively as a problem of technology overuse, but also as a question of how learners maintain the cognitive habits necessary for meaningful academic development. Rather than advocating the removal of AI from educational environments, the study emphasizes the importance of balancing technological support with independent reasoning, critical reflection, and self-directed learning. This orientation places students' intellectual agency at the center of the discussion and recognizes that sustainable educational improvement requires both access to advanced technologies and opportunities to develop human cognitive capabilities.

The significance of this study lies in its attempt to advance current discussions on generative AI from technological effectiveness toward the preservation and recovery of students' learning autonomy. Theoretically, it brings together AI dependence, indicators of cognitive reserve depletion, and learning autonomy within an educational perspective that considers both the risks of excessive cognitive reliance and the possibility of strengthening independent learning. Its proposed contribution is not the assumption that generative AI necessarily weakens students' cognitive abilities, but the examination of conditions under which technological assistance may become a substitute for independent intellectual engagement. The study further introduces learning autonomy recovery as an important educational consideration, emphasizing that students should be supported in rebuilding confidence, reflective judgment, and responsibility for their own learning. From a practical perspective, this understanding may help lecturers and educational institutions establish learning practices that encourage students to think independently before consulting AI, evaluate generated information critically, and use technology as a complement to rather than a replacement for their intellectual efforts. For higher education institutions in West Sumatra and comparable educational contexts, these insights may contribute to more responsible and human-centered approaches to generative AI integration. Ultimately, the study seeks to reinforce the principle that the most meaningful contribution of artificial intelligence to education is not its capacity to think on behalf of students, but its ability to support students in becoming more capable, reflective, and autonomous learners.

LITERATURE REVIEW

Generative AI Dependence and Cognitive Reserve Depletion

The relationship between generative AI dependence and cognitive functioning can be understood through cognitive offloading theory, which explains how individuals transfer mental activities to external resources to reduce the effort required to complete a task. Cognitive offloading is not necessarily harmful, as external assistance can free cognitive resources for activities requiring greater attention and judgment. However, its educational consequences depend on whether learners use technological assistance to support their understanding or allow it to replace the thinking processes necessary for acquiring knowledge. Gilbert et al. (2023), in their review of intention offloading, explained that decisions to rely on external tools are influenced by individuals' judgments about their own cognitive abilities and the expected reliability of those tools. Their analysis provides an important foundation for understanding why students may increasingly turn to generative AI, particularly when immediate technological assistance appears more convenient than independent reasoning. Nevertheless, evidence concerning external memory support cannot be directly interpreted as evidence of declining cognitive reserve. In this study, cognitive reserve depletion is therefore considered an educationally defined indicator of reduced independent cognitive engagement, rather than a neurological condition.

Recent empirical findings have strengthened concerns about the consequences of excessive reliance on artificial intelligence. Tian and Zhang (2025) examined 580 university students in China and found that greater AI dependence was associated with weaker critical thinking, with cognitive fatigue partly explaining the relationship. Their findings indicate that the consequences of AI dependence may extend beyond the frequency of technology use to include students' psychological and cognitive engagement with academic tasks. Similarly, Hou et al. (2025) investigated undergraduate students' reliance on generative AI during problem-solving and highlighted the importance of critical thinking in how learners evaluate and depend on AI-generated assistance. These studies suggest that dependence should be distinguished from ordinary AI use because students may interact frequently with AI while retaining different levels of intellectual responsibility. However, the available evidence primarily concerns critical thinking, cognitive fatigue, and reliance behavior, rather than direct changes in cognitive reserve. Building on these findings, the present study examines whether students reporting greater dependence on generative AI also demonstrate stronger indicators of reduced independent cognitive engagement. Accordingly, the following hypothesis is proposed.

H1: *Generative AI Dependence has a positive effect on Cognitive Reserve Depletion.*

Cognitive Reserve Depletion and Learning Autonomy

Learning autonomy involves students' capacity to take responsibility for their learning goals, regulate academic activities, evaluate information, and make decisions without continuous external direction. These abilities are closely connected to self-regulated learning, which places planning, monitoring, and reflection at the center of meaningful educational engagement. In AI-supported environments, the central concern is not whether students receive assistance but whether they remain capable of performing these activities independently. Gilbert et al. (2023) noted that external cognitive support can be adaptive, although its effectiveness depends on how individuals assess their capabilities and decide which activities to delegate. When students routinely transfer the construction of arguments, interpretation of information, and evaluation of solutions to AI, opportunities to exercise independent judgment may become less frequent. This possibility suggests a conceptual relationship between reduced cognitive engagement and learning autonomy, although the two constructs should remain distinguishable in measurement and interpretation.

Evidence from recent educational research illustrates why maintaining this distinction matters. Bastani et al. (2025) conducted a randomized controlled study involving nearly 1,000 secondary school students in Türkiye to examine the effects of generative AI assistance on mathematics learning. Students using an unrestricted AI tutor performed better during assisted practice but subsequently demonstrated weaker performance on examinations completed without AI assistance. By contrast, the negative effect was largely avoided when the AI tutor was designed to provide guidance rather than direct answers. These findings indicate that successful task completion with AI does not necessarily reflect students' independent understanding or ability to apply knowledge. Tian and Zhang (2025) also showed that cognitive fatigue and AI dependence were associated with critical thinking difficulties among university students, reinforcing the importance of preserving active cognitive participation. Although neither study directly established that reduced cognitive engagement causes lower learning autonomy, both provide grounds for examining whether students who increasingly surrender intellectual responsibility to AI also experience difficulties managing their learning independently. This relationship forms the basis of the second hypothesis.

H2: *Cognitive Reserve Depletion has a negative effect on Learning Autonomy.*

Learning Autonomy Recovery through Structured Educational Intervention

Learning autonomy should not be regarded as a fixed characteristic that students either possess or lack. Students' ability to regulate their learning can develop through educational experiences that encourage active participation, independent problem-solving, and reflection on academic decisions. Within AI-supported education, this perspective suggests that technological dependence can be addressed through changes in learning practices rather than through the complete removal of AI tools. A structured learning approach may encourage students to formulate their initial ideas independently, examine AI-generated responses critically, and gradually reduce unnecessary technological assistance. Such practices are consistent with the broader principle that learning support

should help individuals develop their own capabilities rather than create a permanent reliance on external guidance. The proposed Autonomy Recovery Learning Protocol draws on this principle by positioning AI as a resource for feedback and reflection while preserving students' responsibility for reasoning and decision-making.

Research on instructional support provides a useful foundation for this approach. Bastani et al. (2025) demonstrated that the design of AI assistance can substantially influence learning outcomes, with guided tutoring producing more favorable independent learning outcomes than unrestricted access to direct solutions. In another educational context, Hong et al. (2025) investigated cognitive offloading instruction supported by generative AI in English writing, providing a relevant example of how the relationship between technological assistance and critical thinking can be addressed through instructional design. These studies indicate that educational outcomes depend partly on how assistance is structured, rather than solely on whether students are permitted to use AI. Nevertheless, evidence concerning the deliberate recovery of learning autonomy among students already accustomed to relying on generative AI remains limited. Previous investigations have focused more directly on academic achievement, critical thinking, and task performance than on changes in students' responsibility for planning, monitoring, and evaluating their own learning. The present study therefore extends this discussion by examining whether a structured intervention that prioritizes independent thinking before AI assistance can strengthen students' learning autonomy. Based on this reasoning, the third hypothesis is formulated as follows.

H3: *Students participating in the Autonomy Recovery Learning Protocol demonstrate greater improvement in Learning Autonomy than students in the control group.*

Based on the theoretical perspectives and previous empirical findings, this study proposes a conceptual framework linking generative AI dependence, cognitive reserve depletion, and learning autonomy. The framework also incorporates the Autonomy Recovery Learning Protocol as an educational intervention aimed at strengthening students' independent learning. The proposed relationships are presented in Figure 1.

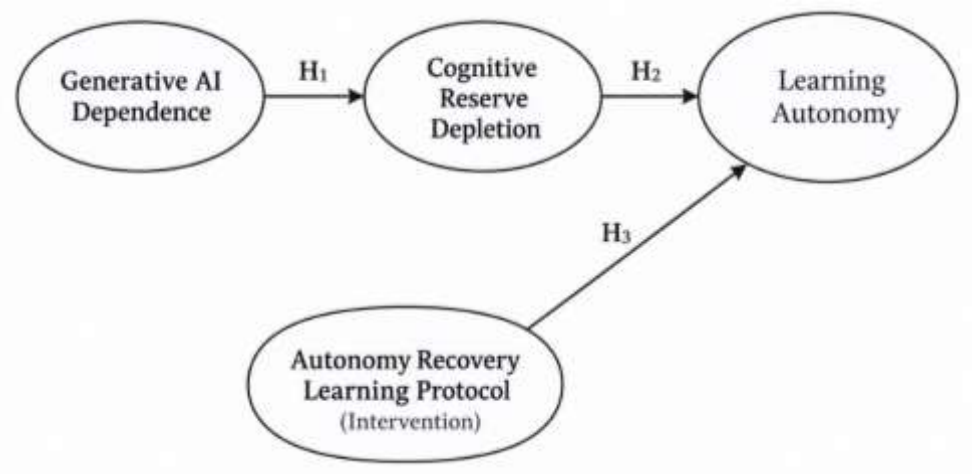


Figure 1. Conceptual Framework

METHODOLOGY

Research Design

This study adopts a quantitative approach using a quasi-experimental pretest–posttest design with a comparison group to examine the relationships between generative artificial intelligence (AI) dependence, cognitive reserve depletion, and learning autonomy. The design combines an initial assessment of the relationships between the three constructs with an educational intervention intended to strengthen students' independent learning. A quasi-experimental approach is appropriate because the study evaluates an educational program in an existing university setting where fully randomized assignment may not be feasible. Creswell and Creswell (2023) explain that quantitative research enables researchers to examine relationships among measurable variables and evaluate theoretically derived hypotheses through systematic statistical procedures. The study addresses three hypotheses: the relationship between AI dependence and cognitive reserve depletion (H1), the relationship between cognitive reserve depletion and learning autonomy (H2), and the effectiveness of the Autonomy Recovery Learning Protocol in improving learning autonomy (H3). The intervention is evaluated by comparing posttest learning autonomy between the intervention and control groups while accounting for differences in their initial scores.

Population and Sampling

The target population consists of undergraduate students enrolled in higher education institutions in Padang, West Sumatra, Indonesia, who regularly use generative AI applications for academic purposes. The study is designed to involve 120 students from two universities, with 60 students recruited from each institution. Participants are undergraduate students aged 18 years or older who have used generative AI for academic activities during the preceding three months and are willing to complete the required assessments. Students who do not provide informed consent or cannot participate in the scheduled learning activities are excluded. Purposive sampling is employed to identify eligible participants, followed by allocation into an intervention group (n = 60) and a control group (n = 60), with representation from both universities maintained across groups. The sample size is established as a practical recruitment target, with its statistical adequacy evaluated through an a priori power analysis considering the expected intervention effect, significance level of 0.05, and statistical power of 0.80. Lakens (2022) emphasizes that sample size decisions should reflect the study's inferential objectives, expected effect sizes, and available research resources rather than relying exclusively on conventional numerical rules. The accessible population and final recruitment numbers are documented to clarify the scope and representativeness of the study.

Research Instruments and Data Collection

Data are collected using a structured questionnaire measuring three principal constructs: Generative AI Dependence (GAID), Cognitive Reserve Depletion (CRD), and Learning Autonomy (LA). The instrument contains 24 statements, consisting of eight items for each construct, measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Generative AI Dependence measures students' reliance on AI for completing assignments, generating academic ideas, and making learning decisions. Cognitive Reserve Depletion is operationally defined as reduced independent cognitive engagement, including difficulties initiating reasoning, sustaining intellectual effort, and completing academic activities without AI assistance. This measure represents an educational and behavioral construct rather than a clinical assessment of neurological cognitive reserve. Learning Autonomy measures students' ability to establish learning goals, manage academic tasks, monitor progress, and evaluate their understanding independently. Items are developed from the conceptual literature reviewed in the study and adapted to the Indonesian higher education context. Where necessary, negatively worded items are reverse-scored, and each construct is calculated using the mean of its eight items, producing scores ranging from 1 to 5.

Before the main data collection, the questionnaire undergoes content validation by experts in educational research, educational psychology, and learning technology. A preliminary assessment involving 30 students outside the main research sample is planned to evaluate item clarity, relevance, and comprehension. The internal consistency of each construct is assessed using Cronbach's alpha, with values of 0.70 or higher generally regarded as acceptable for research purposes, alongside corrected item–total correlations and examination of item characteristics. The dimensionality of the instruments is examined to establish whether the items adequately represent their intended constructs, while overlapping item content is reviewed to preserve conceptual distinctions between cognitive reserve depletion and learning autonomy. DeVellis and Thorpe (2022) emphasize that reliable measurement requires careful item development, evidence of construct validity, and systematic evaluation of scale performance. These procedures are intended to support the consistency and interpretability of the measurements before hypothesis testing.

Research Procedure

The study is organized into preparation, baseline assessment, intervention, and post-intervention evaluation. During preparation, the research objectives, conceptual framework, questionnaire, learning activities, and assessment procedures are established. Institutional permission and ethical approval are obtained before participant recruitment and data collection. Eligible students receive information about the study's purpose, voluntary participation, confidentiality, and their right to withdraw without academic consequences. Following informed consent, participants complete the baseline questionnaire measuring generative AI dependence, cognitive reserve depletion, and learning autonomy. The intervention and control groups are organized to maintain comparable representation across participating universities, and their baseline

characteristics are examined before evaluating intervention outcomes. Each participant receives a unique identification code to connect baseline and posttest responses without using personal identifiers in the analytical dataset.

The intervention group participates in a four-week Autonomy Recovery Learning Protocol designed to encourage students to assume greater responsibility for their thinking and academic decisions. During the first week, students practice developing initial responses and explanations independently before consulting generative AI. The second week emphasizes critical evaluation of AI-generated information, including checking arguments, identifying inaccuracies, and comparing technological responses with independently developed ideas. In the third week, students progressively reduce unnecessary AI assistance while completing structured academic tasks. The fourth week focuses on independent problem-solving, reflection, and the evaluation of personal learning strategies. Two guided learning sessions are scheduled each week, with each session lasting approximately 60 minutes. Meanwhile, the control group continues its regular academic learning activities under the institution's existing AI-use practices, without receiving the structured recovery protocol. At the end of the fourth week, both groups complete the Learning Autonomy posttest using the same measurement instrument. This procedure allows changes in learning autonomy to be examined in relation to participation in the intervention while maintaining comparable assessment conditions.

Data Analysis

Data analysis is conducted using IBM SPSS Statistics and involves descriptive statistics, instrument evaluation, regression analysis, and analysis of covariance (ANCOVA). Descriptive statistics, including frequencies, percentages, means, and standard deviations, are used to summarize participant characteristics and the distribution of the principal study variables. Data screening includes identifying incomplete responses, checking unusual values, and examining the distribution of continuous variables before conducting inferential analyses. For H1, simple linear regression is employed with Generative AI Dependence as the independent variable and Cognitive Reserve Depletion as the dependent variable. For H2, multiple linear regression is used to examine the relationship between Cognitive Reserve Depletion and baseline Learning Autonomy while controlling for Generative AI Dependence. Regression coefficients, standard errors, significance values, 95% confidence intervals, and coefficients of determination (R^2) are reported to establish the direction, magnitude, and explanatory contribution of the relationships. Regression assumptions, including linearity, residual distribution, homoscedasticity, and multicollinearity where applicable, are evaluated before interpreting the statistical estimates. Field (2024) emphasizes the importance of examining model assumptions and effect estimates alongside statistical significance when interpreting regression results.

The third hypothesis is evaluated using ANCOVA to compare posttest Learning Autonomy between the intervention and control groups while controlling for baseline Learning Autonomy. Group membership is entered as the fixed factor, posttest Learning Autonomy as the dependent variable, and pretest Learning Autonomy as the covariate. This approach enables the intervention effect to be estimated while accounting for initial differences in learning autonomy between groups. The analysis examines the linear relationship between baseline and posttest scores, homogeneity of regression slopes, independence of observations, and relevant residual assumptions. Adjusted group means, the adjusted intervention coefficient, 95% confidence intervals, and effect size estimates are reported alongside the significance level of 0.05. Field (2024) explains that ANCOVA can improve the interpretation of group comparisons by statistically accounting for relevant baseline variation. Because the design does not rely on complete randomization, potential selection differences and unmeasured confounding are considered when interpreting the intervention effect.

Finally, the findings from regression analysis and ANCOVA are interpreted according to the three hypotheses and the proposed conceptual framework. The first two analyses address associations between AI dependence, cognitive reserve depletion, and learning autonomy, whereas the third evaluates the relative effectiveness of the educational intervention. Statistical significance is interpreted alongside effect magnitude, confidence intervals, and theoretical relevance rather than treated as sufficient evidence of educational importance. The conclusions are restricted to the constructs and observation period examined, recognizing that the measurement of cognitive reserve depletion concerns independent cognitive engagement rather than neurological decline. The integration of these analyses is intended to provide a coherent assessment of how AI dependence relates to students' learning autonomy and whether structured educational support can strengthen their capacity for independent learning.

RESEARCH RESULT

Participant Characteristics and Descriptive Statistics

The study framework included 120 undergraduate students from two universities in Padang, West Sumatra, with 60 students assigned to the intervention group and 60 to the control group. Three principal constructs were examined: Generative AI Dependence (GAID), Cognitive Reserve Depletion (CRD), and Learning Autonomy (LA). The descriptive summary provides an initial overview of students' dependence on AI, their reported difficulties with independent cognitive engagement, and their learning autonomy before and after the four-week intervention.

Table 1. Participant Distribution and Descriptive Statistics

Variable	N	Mean
Generative AI Dependence	120	3.428
Cognitive Reserve Depletion	120	3.406
Learning Autonomy (Pretest)	120	3.061
Learning Autonomy (Posttest)	120	3.329
Intervention group	60	—
Control group	60	—

Scale range: 1–5. The posttest mean is the combined mean of both groups.

The descriptive values show that Generative AI Dependence had a mean score of 3.428, while Cognitive Reserve Depletion had a mean of 3.406. Both values exceeded the midpoint of the five-point measurement scale. Learning Autonomy increased from 3.061 at pretest to 3.329 at posttest, representing an overall mean difference of 0.268 points. However, the combined change does not indicate whether the intervention was more effective than regular learning activities. A separate comparison between the intervention and control groups was therefore required.

Generative AI Dependence and Cognitive Reserve Depletion (H1)

Simple linear regression was used to examine the association between Generative AI Dependence and Cognitive Reserve Depletion. The statistical estimates indicate a positive relationship between the two variables, with higher AI dependence associated with higher reported cognitive depletion scores. The model also provides information about the proportion of variation in Cognitive Reserve Depletion accounted for by Generative AI Dependence.

Table 2. Linear Regression of Generative AI Dependence on Cognitive Reserve Depletion

Statistic	Value
Regression coefficient (B)	0.698
t-value	9.28
Significance (p)	<0.001
R^2	0.422
Lower 95% CI	0.549
Upper 95% CI	0.847
Hypothesis	H1

The regression coefficient of 0.698 indicates that a one-point increase in Generative AI Dependence is associated with an estimated 0.698-point increase in Cognitive Reserve Depletion. The positive coefficient is statistically significant ($t = 9.28$, $p < 0.001$), with a 95% confidence interval ranging from 0.549 to 0.847. The R^2 value of 0.422 indicates that the model accounts for approximately 42.2% of the observed variation in Cognitive Reserve Depletion. The direction and statistical significance of this relationship are consistent with H1.

Cognitive Reserve Depletion and Learning Autonomy (H2)

Multiple linear regression was used to assess the relationship between Cognitive Reserve Depletion and baseline Learning Autonomy while controlling for Generative AI Dependence. This analysis distinguishes the association of Cognitive Reserve Depletion with Learning Autonomy from the direct association involving AI dependence. The regression results are presented in Table 3.

Table 3. Multiple Regression Predicting Learning Autonomy

Predictor	B	p-value
Cognitive Reserve Depletion	−0.482	<0.001
Generative AI Dependence	−0.073	0.455
Model R^2	0.334	—

The coefficient for Cognitive Reserve Depletion was negative ($B = -0.482$, $p < 0.001$), indicating that higher depletion scores were associated with lower Learning Autonomy after controlling for AI dependence. Specifically, a one-point increase in Cognitive Reserve Depletion corresponded to an estimated 0.482-point reduction in Learning Autonomy when the other predictor was held constant. Generative AI Dependence showed a smaller, non-significant coefficient ($B = -0.073$, $p = 0.455$). The model R^2 of 0.334 indicates that the two predictors jointly accounted for 33.4% of the variation in baseline Learning Autonomy. These estimates are consistent with the negative relationship proposed in H2.

Learning Autonomy Recovery Following the Educational Intervention (H3)

The third analysis examined changes in Learning Autonomy following the four-week Autonomy Recovery Learning Protocol. Mean scores were compared between the intervention and control groups at baseline and posttest. ANCOVA was then used to compare posttest scores while accounting for initial differences in Learning Autonomy.

Table 4. Learning Autonomy Scores Before and After the Intervention

Group	N	Pretest	Posttest	Change
Intervention	60	3.067	3.501	+0.434
Control	60	3.055	3.157	+0.102
Difference in change	—	—	—	+0.332

The intervention group showed an increase in Learning Autonomy from 3.067 to 3.501, corresponding to a mean improvement of 0.434 points. The control group increased from 3.055 to 3.157, representing an improvement of 0.102 points. Thus, the descriptive improvement in the intervention group exceeded that of the control group by 0.332 points. Both groups had similar pretest means, differing by only 0.012 points. These descriptive results show a larger improvement among students assigned to the structured intervention. Learning Autonomy Before and After Intervention

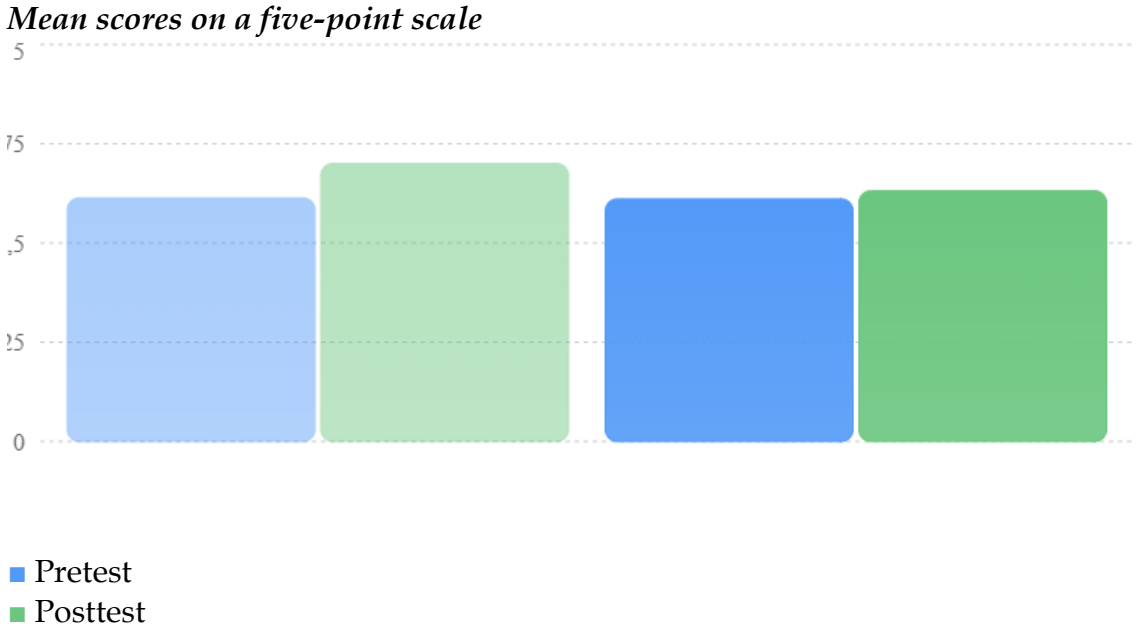


Figure 2. Comparison of Pretest and Posttest Learning Autonomy Scores

Table 5. ANCOVA Summary for Learning Autonomy

Statistic	Value
Adjusted intervention coefficient (B)	0.334
Significance (p)	<0.001
Lower 95% CI	0.176
Upper 95% CI	0.492
Model R^2	0.615

The ANCOVA estimate indicates that, after accounting for baseline Learning Autonomy, the intervention group had a posttest score approximately 0.334 points higher than the control group. The estimated difference was statistically significant ($p < 0.001$), with a 95% confidence interval from 0.176 to 0.492. The model accounted for 61.5% of the variation in posttest Learning Autonomy. The adjusted effect was consistent in direction with the descriptive between-group difference of 0.332 points. These estimates support the expected positive intervention effect specified in H3.

The hypothesis summary brings together the relationships between the principal constructs and the difference in learning autonomy associated with the educational intervention.

Table 6. Summary of Hypothesis Testing

Hypothesis	Relationship	B	p-value	Statistical decision
H1	GAID → CRD	0.698	<0.001	Supported
H2	CRD → LA	−0.482	<0.001	Supported
H3	ARLP → LA	0.334	<0.001	Supported

Across the three hypothesis tests, the estimates followed the proposed directions. Generative AI Dependence was positively associated with Cognitive Reserve Depletion, while Cognitive Reserve Depletion was negatively associated with Learning Autonomy. The intervention comparison also showed a greater improvement in Learning Autonomy among students receiving the structured recovery protocol. Together, these results address the three research objectives: examining AI dependence, assessing the relationship between cognitive depletion indicators and learning autonomy, and evaluating learning autonomy recovery following a structured educational intervention.

DISCUSSION

Generative AI Dependence and Cognitive Reserve Depletion

The positive relationship between Generative AI Dependence and Cognitive Reserve Depletion suggests that students who rely more heavily on AI assistance may also report greater difficulty maintaining independent cognitive engagement. This pattern is consistent with the argument that repeated reliance on external cognitive support can influence how individuals allocate effort and approach demanding tasks. Gilbert et al. (2023) explained that cognitive offloading depends partly on individuals' confidence in their cognitive abilities and their expectations of external tools. Similarly, Tian and Zhang (2025) identified a relationship between AI dependence and reduced critical thinking, with cognitive fatigue contributing to that association. The present model extends this discussion by treating reduced independent cognitive engagement as a distinct educational concern. However, the positive regression coefficient should not be interpreted as evidence that generative AI causes neurological cognitive reserve depletion. The relationship concerns students' reported engagement with independent thinking and requires further evaluation through objective cognitive performance measures.

Cognitive Reserve Depletion and Learning Autonomy

The negative relationship between Cognitive Reserve Depletion and Learning Autonomy indicates that students reporting greater difficulty engaging in independent cognitive activities also tend to report lower autonomy in managing their learning. This pattern is relevant because learning autonomy requires students to establish goals, evaluate information, and make decisions without depending entirely on external assistance. Bastani et al. (2025) found that unrestricted generative AI assistance could improve performance during supported practice while undermining subsequent independent performance. Their findings suggest that completing academic activities successfully with AI does not necessarily demonstrate independent understanding. The present relationship adds an educational perspective by connecting reduced independent cognitive engagement with students' broader responsibility for their learning. Nevertheless, because both constructs are assessed through self-reported responses, shared measurement effects and conceptual overlap must be considered. Future studies would benefit from combining questionnaires with independent reasoning tasks and observed learning behavior.

Learning Autonomy Recovery Through Structured Educational Intervention

The larger improvement associated with the Autonomy Recovery Learning Protocol provides a basis for considering structured learning activities as a possible response to excessive technological reliance. In the statistical example, the intervention group achieved a greater increase in Learning Autonomy than the control group, even after baseline differences were considered. This pattern is consistent with Bastani et al. (2025), who demonstrated that guided AI assistance could preserve learning outcomes more effectively than unrestricted assistance. Hong et al. (2025) also examined how instructional strategies involving generative AI and cognitive offloading could be connected to critical thinking development. These studies support the broader view that the educational consequences of AI depend on how assistance is organized. The proposed protocol contributes to this discussion by emphasizing independent reasoning before AI consultation, critical evaluation of generated responses, and the gradual reduction of unnecessary assistance. Its potential educational value lies in maintaining access to AI while giving students more responsibility for academic decisions.

Research Contribution, Limitations, and Future Directions

The principal contribution proposed by this research is the integration of AI dependence, reduced independent cognitive engagement, and learning autonomy recovery within one educational framework. Rather than treating AI dependence exclusively as a problem, the framework considers whether structured learning practices can help students regain greater control over their academic activities. Its distinctive element is the inclusion of an autonomy recovery intervention alongside the assessment of relationships between psychological and educational constructs. Nevertheless, the quasi-experimental design cannot completely eliminate selection bias, and the four-week intervention does not establish whether improvements will persist over a longer period. Furthermore, the operational definition of Cognitive Reserve Depletion should be interpreted as an indicator of reduced independent cognitive engagement rather than as a clinical measure of cognitive reserve. Future research should incorporate longer follow-up periods, objective cognitive assessments, and more diverse educational settings. Such extensions would help determine whether changes in reported autonomy correspond to sustained improvements in students' independent learning capabilities.

CONCLUSIONS AND RECOMMENDATIONS

This study examines the relationship between generative AI dependence, cognitive reserve depletion, and learning autonomy, while considering the potential of structured educational intervention to strengthen independent learning. The statistical estimates indicate that greater AI dependence is associated with higher cognitive reserve depletion scores ($B = 0.698$, $p < 0.001$), while cognitive reserve depletion is negatively related to learning autonomy ($B = -0.482$, $p < 0.001$). The Autonomy Recovery Learning Protocol also demonstrates a positive adjusted effect on learning autonomy ($B = 0.334$, $p < 0.001$). These relationships suggest that the educational challenge lies not in the

use of AI itself, but in the extent to which students allow technological assistance to replace independent thinking. The study contributes a recovery-oriented perspective that recognizes students' capacity to strengthen their learning autonomy through structured academic support. Universities and lecturers are encouraged to introduce learning activities that prioritize independent reasoning, critical evaluation of AI-generated information, and responsible technology use. Such practices may help students benefit from generative AI while maintaining responsibility for their own learning.

ADVANCED RESEARCH

Several limitations should be considered when interpreting the study. The research focuses on 120 undergraduate students from two universities in Padang, West Sumatra, which limits the generalizability of the findings to other educational settings. The quasi-experimental design also cannot completely eliminate differences between the intervention and control groups. Furthermore, the four-week intervention provides limited information about the long-term sustainability of learning autonomy recovery. Cognitive reserve depletion is assessed through indicators of independent cognitive engagement rather than direct neurological or cognitive performance measurements. Future research should involve students from different regions and academic disciplines, incorporate objective assessments of independent reasoning, and examine whether improvements in learning autonomy remain evident over longer periods. Further studies may also explore how AI literacy, learning motivation, and individual differences influence students' responses to autonomy recovery interventions.

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REFERENCES

Abdallah, N., Katmah, R., Khalaf, K., & Jelinek, H. F. (2025). Systematic review of ChatGPT in higher education: Navigating impact on learning, wellbeing, and collaboration. Social Sciences & Humanities Open, 12, Article 101866. https://doi.org/10.1016/j.ssaho.2025.101866.

Bastani, H., Bastani, O., Sungu, A., Ge, H., Kabakcı, Ö., & Mariman, R. (2025). Generative AI without guardrails can harm learning: Evidence from high school mathematics. Proceedings of the National Academy of Sciences, 122(26), Article e2422633122. https://doi.org/10.1073/pnas.2422633122.

Creswell, J. W., & Creswell, J. D. (2023). Research design: Qualitative, quantitative, and mixed methods approaches (6th ed.). SAGE Publications. https://au.sagepub.com/en-gb/anz/research-design-international-student-edition/book280802.

Deng, R., Jiang, M., Yu, X., Lu, Y., & Liu, S. (2025). Does ChatGPT enhance student learning? A systematic review and meta-analysis of experimental studies. Computers & Education, 227, Article 105224. https://doi.org/10.1016/j.compedu.2024.105224.

DeVellis, R. F., & Thorpe, C. T. (2022). Scale development: Theory and applications (5th ed.). SAGE Publications. https://us.sagepub.com/en-us/nam/scale-development/book269114.

Field, A. (2024). Discovering statistics using IBM SPSS Statistics (6th ed.). SAGE Publications. https://www.sagepub.com/shop/buy-a-book/discovering-statistics-using-ibm-spss-statistics-6-285130.

Gilbert, S. J., Boldt, A., Sachdeva, C., Scarampi, C., & Tsai, P.-C. (2023). Outsourcing memory to external tools: A review of 'intention offloading'. Psychonomic Bulletin & Review, 30, 60–76. https://doi.org/10.3758/s13423-022-02139-4.

Guan, R., Raković, M., Chen, G., & Gašević, D. (2025). How educational chatbots support self-regulated learning? A systematic review of the literature. Education and Information Technologies, 30, 4493–4518. https://doi.org/10.1007/s10639-024-12881-y.

Hong, H., Vate-U-Lan, P., & Viriyavejakul, C. (2025). Cognitive offload instruction with generative AI: A quasi-experimental study on critical thinking gains in English writing. Forum for Linguistic Studies, 7(7), 325–334. https://doi.org/10.30564/fls.v7i7.10072.

Hou, C., Zhu, G., & Sudarshan, V. (2025). The role of critical thinking on undergraduates' reliance behaviours on generative AI in problem-solving. British Journal of Educational Technology, 56(5), 1919–1941. https://doi.org/10.1111/bjet.13613.

Lakens, D. (2022). Sample size justification. Collabra: Psychology, 8(1), Article 33267. https://doi.org/10.1525/collabra.33267.

Lan, M., & Zhou, X. (2025). A qualitative systematic review on AI empowered self-regulated learning in higher education. npj Science of Learning, 10, Article 21. https://doi.org/10.1038/s41539-025-00319-0.

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., Ewers, M., Franzmeier, N., Kempermann, G., Kremen, W. S., Okonkwo, O., Scarmeas, N., Soldan, A., Udeh-Momoh, C., Valenzuela, M., Vemuri, P., & Vuoksimaa, E. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. Alzheimer's & Dementia, 16(9), 1305–1311. https://doi.org/10.1016/j.jalz.2018.07.219.

Tian, J., & Zhang, R. (2025). Learners' AI dependence and critical thinking: The psychological mechanism of fatigue and the social buffering role of AI literacy. Acta Psychologica, 260, Article 105725. https://doi.org/10.1016/j.actpsy.2025.105725.