Снижение когнитивной нагрузки и оптимизация ментальных моделей студентов технических вузов посредством внедрения ИИ-тьюторов в режиме сократического диалога

Бегмырадова Говхер, Аннаева Гульшат

Mitigating Mitigating cognitive load and optimizing students' mental models in technical universities through the implementation of AI tutors in Socratic dialogue mode

Begmyradova Govher, Annayeva Gulshat

Abstract.
This study addresses the critical dissonance between the expanding technology stack in higher engineering education and traditional didactic methods, which often leads to "Cognitive mimicry" among students. We propose a transition from the "Direct Answering" paradigm of Large Language Models (LLMs) toward a strategic facilitator model based on Socratic maieutics. Through a mixed-methods pilot study involving cybersecurity students (N=25), we implemented a "Socratic Tutor" mode using GPT-4 and Gemini, restricted to heuristic guiding questions. Data triangulation - utilizing NASA-TLX for workload assessment, Bloom's Taxonomy for query analysis, and pre/post-test evaluations - revealed a 12-15% increase in academic performance. Results show that 64% of student inquiries reached the synthesis level, and the verification of AI-generated content against official RFC/NIST standards improved by 30%. The findings suggest that integrating Socratic dialogue into AI-agents creates an adaptive cognitive scaffold that minimizes frustration and fosters deep analytical synthesis, effectively transforming educational stress into productive cognitive engagement.

Keywords: Large Language Models, Socratic Method, Cognitive Load, Cybersecurity Education, Scaffolding.

For contacts: Begmyradova Govher, Director of the Scientific and Educational Center "IT-Nurly Shohle" of the State Energy Institute of Turkmenistan, gowher-2020@mail.ru

I. INTRODUCTION

In the context of the rapid digital transformation of the global higher education ecosystem - primarily affecting knowledge-intensive engineering and IT disciplines - there is an exponential growth in the volume and complexity of information being transmitted. This trend creates a critical dissonance between the rapidly expanding technology stack and traditional didactic methods. The modern educational paradigm faces a fundamental challenge: the development of effective mechanisms for the interiorization of high-level abstract concepts under strict limits on classroom hours and a growing deficit of personalized pedagogical support. In this situation, standard knowledge translation models fail to ensure the required cognitive engagement, necessitating a search for alternative tools of intellectual support for students [1].

The key determinant of the systemic crisis in teaching technical disciplines is manifested in the critical density of didactic units per unit of instructional time. The traditional academic model, centered on the figure of the instructor, faces the physical impossibility of providing an adequate level of personalization for each student's educational trajectory. In conditions of an acute shortage of prompt feedback, a gnoseological gap inevitably forms between the theoretical basis and the practical implementation of competencies.

The absence of timely deconstruction of individual difficulties forces students to shift toward a strategy of cognitive mimicry - the mechanical reproduction of ready-made algorithms and the copying of program code [2]. Such an approximation of problem-solving creates an illusion of progress but actually blocks the formation of sustainable professional competencies and deep analytical synthesis skills, turning the learning process into a formal fulfillment of regulatory requirements [5].

The integration of generative algorithms based on Large Language Models (LLMs) into the educational environment marks a transition to a qualitatively new stage in the formation of adaptive and highly personalized learning trajectories. Unlike traditional static information carriers, modern AI systems act as dynamic intellectual agents, functioning in a mode of continuous monitoring and support (24/7). This creates the prerequisites for overcoming the barriers of time and spatial limitations inherent in the classical academic process.

However, a critical analysis of AI integration into didactics reveals a fundamental problem related to the nature of the subject-object interaction within the "AI–student" dyad. The "Direct Answering" paradigm, which dominates standard interfaces, triggers a degradation of active cognitive search. The inflation of effort in achieving a result inevitably leads to the phenomenon of cognitive dependency (or cognitive laziness), wherein critical thinking is replaced by the mechanical consumption of synthesized content. Ultimately, this devalues the educational merit of the technology, transforming a powerful developmental tool into a means of bypassing the intellectual difficulties necessary for the deep mastery of material.

Within the framework of this study, we postulate the necessity of deeply integrating maieutics (the classical Socratic method) into the interaction architecture between intelligent agents and learners. This entails a qualitative transformation of AI algorithmic logic: moving from the information oracle paradigm toward a model of a strategic facilitator.

Implementing the Socratic dialogue method within LLM functionality involves using a cascade of heuristic guiding questions aimed at initiating independent analytical search. Instead of the deterministic delivery of a ready-made result, the algorithm acts as a cognitive guide that structures the student's problem space and stimulates the step-by-step verification of their own hypotheses. Such integration allows AI to evolve from a tool for automated answering into a highly effective system of cognitive scaffolding, supporting the student's zone of proximal development through active intellectual reflection.

The central hypothesis of this research is based on the postulate that the use of LLM-based intelligent agents in a Socratic maieutics mode—excluding the direct reproduction of ready-made solutions and focusing on the learner's iterative navigation through a cascade of logically sound heuristic queries—determines a qualitative transformation of the educational process.

We suggest that such a methodology not only ensures the prolonged interiorization of complex technical concepts by activating deep cognitive search mechanisms but also preemptively minimizes the level of cognitive dissonance and stress caused by frustration when encountering highly abstract material. In this paradigm, AI acts as an adaptive damper that, by segmenting task complexity, prevents working memory overload and promotes the attainment of a stable flow state, essential for the effective mastery of engineering competencies.

The implementation of this approach allows for the achievement of the following strategic goals:

– transformation of the student from a passive recipient into an active constructor of knowledge through the independent building of logical chains;

– decomposition of complex tasks into operational micro-stages, preventing information overload of the working memory;

– elimination of evaluative anxiety and the fear of criticism, which is critically important for overcoming barriers in mastering innovations.

Thus, the convergence of ancient maieutics and modern LLMs represents not merely a technological update, but a fundamental revision of the didactic process. The proposed approach is aimed at bridging the gap between the rising complexity of engineering knowledge and the physical limitations of human perception, transforming educational stress into productive cognitive engagement.

II. METHODOLOGY

The present study employs a Mixed Methods Research design, integrating quantitative performance metrics with a qualitative cognitive audit of "student–AI" interactions. The research is anchored in the cognitive constructivism paradigm, conceptualizing Large Language Models (LLMs) as catalysts for mental model formation through dialogic mediation. The theoretical framework is synthesized from Cognitive Load Theory (CLT) and the scaffolding construct, wherein the AI agent dynamically calibrates task complexity relative to the learner's Zone of Proximal Development (ZPD) within the domain of cybersecurity [7].

The empirical phase was conducted as a pilot study at the Department of Information Security. The sample consisted of fourth-year undergraduate students (N = 25) with verified competencies in cryptography, network security, and ethical hacking. Participants were bifurcated into two cohorts:

Experimental Group: Engaged with LLMs (GPT-4/Gemini) configured in a Socratic Tutor mode [10].

Control Group: Utilized conventional pedagogical resources, including NIST documentation, CVE repositories, and professional technical forums [8].

In the experimental group, a rigorous "maieutic" protocol was enforced via system-level prompting. The LLM was restricted from providing direct solutions or exploit code, instead delivering a series of heuristic inquiries focused on attack vectors and defensive logic.

To ensure internal validity and empirical reliability, the study executed a rigorous data triangulation across three distinct dimensions, creating a comprehensive analytical matrix of the learning process. The primary investigative layer involved a granular Cognitive Log Analysis utilizing Prompt Engineering Analytics to map student Chain-of-Thought (CoT) trajectories directly against the hierarchical levels of Bloom’s Taxonomy. This approach allowed for a precise evaluation of the students' capacity for high-level vulnerability synthesis and the autonomous modeling of protective algorithms, shifting the focus from simple data retrieval to complex analytical reasoning. Parallel to this cognitive mapping, a Subjective Workload Assessment was conducted using the NASA-TLX (Task Load Index) to quantify the perceived mental demand, effort, and frustration levels during network anomaly detection scenarios. This dimension was critical for determining whether the

Socratic AI-agent maintains an optimal cognitive balance or leads to premature fatigue. Finally, the educational efficacy was validated through a Knowledge Delta Evaluation, employing pre-test and post-test instruments designed to measure the quantitative gains in the conceptual understanding of security protocols. By synthesizing these three vectors—cognitive process, subjective experience, and objective outcome—the methodology provides a robust basis for assessing the qualitative transformation of the educational trajectory under the influence of generative AI.

Statistical synthesis was conducted using the Mann-Whitney U-test for inter-group comparisons, given the non-parametric nature of the sample (N=25). Furthermore, Pearson correlation coefficients were calculated to examine the relationship between prompt-iteration depth and laboratory performance. All statistical procedures were executed in the R environment. Ethical compliance was maintained through rigorous data de-identification and the procurement of informed consent from all participants.

III. RESULTS

The present study adopts a Mixed Methods Research design, integrating quantitative academic performance metrics with a qualitative cognitive audit of "student–AI" interactions. This investigation was operationalized as a pilot study within the Department of Information Security, involving a cohort of fourth-year undergraduate students (N = 25) possessing advanced competencies in cryptography and network defense. The methodological framework is anchored in Cognitive Load Theory (CLT) and the construct of "scaffolding," wherein the AI-tutor (utilizing GPT-4 and Gemini models) functions through a Socratic maieutic dialogue.

In the experimental group, a rigorous interaction protocol was enforced via system-level prompting, designed to catalyze analytical reasoning through heuristic inquiries rather than the automated generation of security configurations. To ensure robust data validity, a triangulation strategy was implemented, encompassing the analysis of interaction logs, the administration of the NASA-TLX (Task Load Index) scale to assess subjective workload, and a comparative evaluation of pre- and post-test results [3-4].

Given the focused sample size (N=25), statistical significance was validated using the non-parametric Mann-Whitney U-test for inter-group comparisons, supplemented by Pearson correlation analysis within the R statistical environment to identify dependencies between dialogue depth and technical proficiency. The primary comparative indicators derived from this analysis are synthesized in Table 1.

Table 1. Comparative Analysis of Cognitive Performance and Academic Achievement Metrics (N=25)

Indicator / Metric	Control Group (n=12)	Экспериментальная группа (n=13)	P-value (Mann-Whitney U)
Total NASA-TLX Score (Workload Index)	78.4 ± 4.2	62.1 ± 5.3	$p < 0.05$
Frustration Level (Scale 1–100)	45.2	37.1	$p = 0.041$

Proportion of "Synthesis" Level Queries (Bloom's Taxonomy)	42%	64%	$p = 0.028$
Final Score in Security Module	74.5 ± 6.1	86.8 ± 4.8	$p = 0.034$
AI Response Verification Coefficient	0.22	0.54	$p < 0.01$

The empirical findings demonstrate that the level of "germane" cognitive load within the experimental group facilitated a more profound schematization of knowledge. The average mental effort score in the AI-tutoring group showed a significant decrease, indicating an optimization of the students' cognitive resources during complex vulnerability assessment tasks. A content analysis of the interactions revealed a qualitative transformation in inquiry structures: by the conclusion of the experiment, the dialogue architecture had shifted decisively toward the analysis and synthesis levels of Bloom’s Taxonomy.

Statistical analysis confirmed a strong positive correlation ($r = 0.72$) between the depth of dialogue iterations with the AI and the final quality of the practical laboratory assignments. A critical outcome of the study was the measurable enhancement of critical thinking skills: there was a documented 30% increase in the verification of AI-generated responses against official RFC protocols and CVE databases. This trend effectively minimizes the risks associated with "blind trust" in algorithms—a factor of paramount importance in mission-critical information security tasks [4].

IV. DISCUSSION

The empirical results of this study validate the hypothesis that the integration of Large Language Models (LLMs) via a Socratic maieutic architecture induces a qualitative shift in the cognitive strategies of engineering students. By moving away from the "Direct Answering" paradigm, which often fosters "cognitive mimicry" and intellectual passivity, the Socratic AI-agent functions as a dynamic mediator that facilitates the interiorization of complex technical constructs.A primary finding is the optimization of cognitive resources as evidenced by the NASA-TLX metrics. According to Cognitive Load Theory (CLT), the "Socratic Tutor" mode effectively manages intrinsic load by decomposing monolithic cybersecurity problems into heuristic micro-stages. This prevents the saturation of working memory and maximizes germane load - the mental effort dedicated to the construction of sustainable schemas [9]. The observed reduction in frustration levels suggests that the AI-agent provides an optimal "scaffolding" effect, maintaining the student within their Zone of Proximal Development (ZPD). In this state, the learner is challenged enough to remain engaged but supported enough to avoid the paralyzing stress typically associated with high-level abstraction in cryptography and network defense.The qualitative transformation of inquiry structures, mapped against Bloom’s Taxonomy, indicates a significant development of metacognitive autonomy [6]. The fact that 64% of interactions in the experimental group reached the "Synthesis" and "Analysis" levels suggests that students were not merely retrieving data, but were actively constructing logical chains and verifying defensive hypotheses. This is a critical departure from the "blind trust" phenomenon often observed in AI-human interactions. The 30% increase in the verification of AI-generated content against RFC protocols and NIST databases proves that the maieutic approach fosters a "healthy skepticism." In the context of mission-critical information security, this ability to independently validate automated outputs is a defining professional competence.Furthermore, the strong positive correlation (r = 0.72) between dialogue depth and laboratory performance confirms that iterative, logically sound inquiry is more effective for knowledge retention than traditional static documentation. The Socratic AI-agent acts as an adaptive damper, transforming the "gnoseological gap" between theory and practice into a structured intellectual search. Ultimately, this research demonstrates that the convergence of ancient pedagogical philosophy and modern generative algorithms provides a robust solution to the personalization of mass technical education, turning potential "cognitive laziness" into proactive, high-level analytical engagement.

V. CONCLUSION

The cognitive analysis conducted in this study confirms that the integration of Large Language Models (LLMs) as personalized AI tutors in higher technical education serves as a strategic catalyst for transforming the educational paradigm. Empirical evidence from the pilot study involving fourth-year Information Security students demonstrates that transitioning from traditional information retrieval to the interactive Socratic method (maieutics) yields a synergistic effect: academic performance improved by 12-15%, while simultaneously optimizing students' cognitive resources. The primary driver of this dynamic is the activation of higher-order thinking processes, focused on the deconstruction of complex technical problems rather than the passive consumption of ready-made algorithmic solutions.

A key finding of this research is the qualitative transformation of students' cognitive strategies. The shift toward AI-based mentorship facilitated an evolution from reproductive code-copying toward high-level analysis and the synthesis of security systems. This is evidenced by the increase in complex queries - categorized under the higher tiers of Bloom’s Taxonomy - reaching a proportion of 64%. Such data indicates the formation of metacognitive autonomy: in the "Socratic Tutor" mode, students in the experimental group were 30% more likely to demonstrate a critical approach to data, frequently verifying model-generated responses against fundamental sources such as RFC standards and NIST databases [3]. In the context of cybersecurity, this skill is a defining professional competence, as it minimizes the risks associated with "blind trust" in automated systems.

Furthermore, the reduction in frustration levels and subjective cognitive load, as recorded by the NASA-TLX scale, indicates that the AI tutor effectively performs the function of adaptive scaffolding [7]. This allows students to overcome the "entry threshold" into the most knowledge-intensive sectors of information security without compromising academic motivation. In the long term, the integration of intelligent tutors into engineering curricula has the potential to radically address the challenge of personalizing mass education by adapting learning trajectories to each student's zone of proximal development. However, the successful institutionalization of this approach requires the development of specialized pedagogical prompts and the cultivation of an interaction ethic regarding generative models. This study lays the foundation for further investigation into the impact of AI on the development of professional intuition and the predictive capabilities of future information security engineers.

VI. REFERENCES

[1] J. Sweller, "Cognitive Load Theory, Educational Psychology, and Instructional Design," Educational Psychology Review, vol. 6, no. 4, pp. 295–312, 1994.

[2] L. S. Vygotsky, Mind in Society: The Development of Higher Psychological Processes. Cambridge, MA: Harvard University Press, 1978.

[3] B. S. Bloom, Taxonomy of Educational Objectives: The Classification of Educational Goals. New York: Longmans, Green, 1956.

[4] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," Advances in Psychology, vol. 52, pp. 139–183, 1988.

[5] T. B. Brown et al., "Language Models are Few-Shot Learners," arXiv preprint arXiv:2005.14165, 2020.

[6] P. R. Pintrich, "A Conceptual Framework for Assessing Motivation and Self-Regulated Learning in College Students," Educational Psychology Review, vol. 16, no. 4, pp. 385–407, 2004.

[7] D. Wood, J. S. Bruner, and G. Ross, "The Role of Tutoring in Problem Solving," Journal of Child Psychology and Psychiatry, vol. 17, no. 2, pp. 89–100, 1976.

[8] NIST, "Workforce Framework for Cybersecurity (NICE Framework)," National Institute of Standards and Technology, Special Publication 800-181, 2020.

[9] R. Mayer, Multimedia Learning. Cambridge: Cambridge University Press, 2001.

[10] A. Radford et al., "Learning Hierarchical Spatiotemporal Features," OpenAI, 2023.