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Designing a Knowledge Graph-Based Personalized Learning Framework for Higher-Order Thinking in Linear Algebra: A Mixed-Methods Needs Analysis

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Abstract

As an essential basic course in institutions of higher education, Linear Algebra exerts a direct influence on the cultivation of students' comprehensive skills and overall literacy. To identify the existing problems in Linear Algebra teaching as well as the actual demands of teachers and students, this study adopts a mixed research method combining semi-structured interviews with teachers and questionnaires for students to conduct a comprehensive demand analysis on the current teaching situation of Linear Algebra. In this research, 12 frontline teachers and teaching administrators were interviewed, and 606 valid student questionnaires were collected. Through systematic analysis of qualitative and quantitative data, the core demands of teachers and students were sorted out. The results show that students have strong demands for visualized learning resources, personalized learning support, higher-order thinking training and emotional support. Meanwhile, teachers are in urgent need of structured knowledge organization tools, differentiated teaching strategies, higher-order thinking task resources and intelligent teaching management support. On this basis, the functional demands of the knowledge graph-based personalized learning model for cultivating students' higher-order thinking skills are clarified. In addition, this study has certain limitations such as limited research samples and untested demand system in practical teaching. Future research will expand the research scope, complete the design, development and experimental verification of the personalized learning model, so as to optimize the teaching effect of Linear Algebra and effectively improve students' higher-order thinking skills.

Keywords: Linear Algebra, Demand Analysis, Knowledge Graph, Personalised Learning, Higher-order Thinking Skills

Introduction

Today’s world competition is essentially a competition of innovation ability. Cultivating innovative talents is a major national project, and higher-order thinking skills are the key foundation of students’ creativity, so it is especially important to improve students’ higher-order thinking skills. Higher-order thinking skills are closely related to the skills needed in the

21st century, and the development of higher-order thinking skills in students can help them face global challenges (Bahri et al., 2021). Such skills mainly refer to students' ability to analyze, evaluate and create (Kusumaningtyas et al., 2024). Education is an important means of developing high quality human resources and is often regarded as a key area of national development. Mathematics is seen as a discipline with great potential that can help optimize the cultivation of human resources (Sari, 2018; Widodo et al., 2023). Relevant studies have confirmed that personalised learning conditions and environments exert a significant positive effect on promoting the development of students' higher-order thinking skills (Xie et al., 2024).

However, test results from the Program for International Student Assessment (PISA) show that Chinese students, while demonstrating solid basic knowledge and skills, performed poorly in complex cognitive skills including higher-order thinking and collaborative problem solving (Yang & Fan, 2020). Traditional classroom instruction and one-size-fits-all teaching modes focus excessively on knowledge transfer and unified teaching arrangements, setting identical teaching objectives for all learners. This teaching mode ignores individual learning differences, makes students passive recipients of knowledge, and fails to provide sufficient opportunities for independent experiential learning. It restricts students' deep thinking and in-depth problem exploration, and ultimately hinders the effective cultivation of higher-order thinking skills (Bhutoria, 2022). In recent years, plenty of scholars have put forward diversified teaching reform strategies, which have promoted the development of personalised education to a certain extent (Gao & Sang, 2020; Zhang, 2024). Even so, there are still prominent difficulties in the practical cultivation of students' higher-order thinking skills (Bhutoria, 2022; Zhang, 2024; Sanal et al., 2025). Particularly for abstract and logic-intensive courses such as Linear Algebra, there is still a lack of sufficient practical research on how to design targeted learning tasks suitable for different student groups, so as to realise the cultivation of higher-order thinking skills via personalised learning (Wu et al., 2022).

In view of the above practical dilemmas and research gaps, this study takes the needs analysis as the core research orientation. The ultimate goal of the whole research was to construct a Knowledge Graph-Based Personalised Learning Model for cultivating students' higher-order thinking skills in Linear Algebra teaching. To ensure that the subsequent model design is practical, targeted and in line with real classroom situations, it is essential to fully investigate and sort out the actual teaching demands of teachers and authentic learning needs of students in advance.

In the follow-up model construction, all design contents need to take students' actual learning goals as the core guideline, fully combine course characteristics and individual student differences, and match suitable learning resources, personalised learning paths and classroom learning activities according to students' cognitive level, mathematical foundation and actual learning demands, so as to steadily promote the improvement of learners' higher-order thinking skills. Therefore, carrying out systematic needs investigation and analysis is the essential preliminary work and solid premise for the smooth implementation of the whole research.

Research Design

This study aimed to explore the actual situation and practical demands of Linear Algebra teaching and learning, especially the existing difficulties and expectations in cultivating students' higher-order thinking skills and implementing personalised learning. It adopted parallel mixed methods for needs analysis, combining qualitative and quantitative research to lay an empirical foundation for constructing the personalised learning model.

Semi-structured interviews were carried out with Linear Algebra teachers and educational administrators. The interview contents covered teaching goals, strategies for developing higher-order thinking, application of teaching resources, practical difficulties and personalised learning support modes. As a typical qualitative research method, semi-structured interviews enabled researchers to sort out core themes and allowed interviewees to express their practical experience and professional opinions freely (Patton, 2015). This method has been widely applied in studies on teaching practice, curriculum reform and educational technology application (Cohen et al., 2018). The interview results also facilitated data complementation and triangulation in mixed methods research (Creswell & Plano Clark, 2018).

Meanwhile, structured questionnaires were designed and issued to students taking Linear Algebra courses. The questionnaire investigated students' learning status, knowledge mastery, thinking ability development, use of teaching resources and personalised learning demands. It also explored students' learning difficulties, recognition of personalised learning models, and self-assessment on higher-order thinking skills including analysis, evaluation and creation (Anderson & Krathwohl, 2001). Questionnaires were effective in collecting quantitative data on students' learning behaviours and learning demands (Dillman et al., 2014). Referring to previous research, the questionnaire also surveyed students' attitudes and expectations towards personalised learning based on individual learning characteristics.

In general, this study combined semi-structured interviews and questionnaires. The two types of data were collected simultaneously and analysed separately for mutual verification. The research clarified practical problems and actual learning demands from both teachers' and students' perspectives, which provided practical support for the follow-up construction of knowledge graph-based personalised learning model. Methodological triangulation was used to compare and interpret all data comprehensively, so as to improve the reliability and validity of research results (Denzin, 1978; Flick, 2018).

Survey Results and Analysis

Thematic Analysis Results of Semi-Structured Teacher Interviews

Semi-structured interviews with Linear Algebra teachers and educational administrators revealed key insights into teaching practice, focusing on four core aspects related to higher-order thinking cultivation and personalised learning, as follows:

(1) Knowledge Map Construction and Presentation

Knowledge map construction is core to Linear Algebra personalised teaching. It requires decomposing the course into core knowledge points, clarifying their hierarchical relationships, prerequisite knowledge, confusing concepts, and logical connections, then visualising these into intuitive diagrams. Complex content can be broken into modules with dynamic

demonstrations to enhance comprehension. This helps teachers refine instructional logic and students build systematic knowledge frameworks, while dynamically recommending learning resources based on individual gaps.

(2) Personalised Learning Pathways and Task Recommendations

Personalised learning pathways and task recommendations accommodate student differences by first assessing students' proficiency, cognitive characteristics, and learning preferences, then constructing comprehensive learner profiles. Bespoke, dynamically adjusted pathways are designed—remedial for weaker students and enrichment for advanced learners—aligned with individual discipline needs. Task recommendations progress from foundational to advanced, focusing on both knowledge reinforcement and higher-order thinking development, with real-time feedback to adjust paths.

(3) Designing Higher-Order Thinking Tasks

Higher-order thinking task design guides students beyond rote memorisation to analysis, reasoning, and modelling. Tasks adhere to Linear Algebra's abstract nature, introducing complex content only after foundational mastery, and target specific higher-order skills. They consider students' cognitive levels to avoid overly easy or difficult tasks, integrate real-world applications and discipline needs, and include dynamic feedback to adjust in real-time.

(4) Sustaining Interest and Emotional Support

Sustaining student interest and providing emotional support are crucial for learning motivation. Teaching content and methods should align with students' contexts, demonstrating Linear Algebra's practical utility through discipline-relevant scenarios and interactive tasks. Emotional support involves monitoring students' anxiety, offering targeted encouragement, establishing support mechanisms, and fostering a collaborative classroom atmosphere to prevent negative emotions from hindering learning.

Student Questionnaire Data Analysis

Sample Characteristics and Descriptive Statistical Analysis

Q1. Year/Grade of Respondents

The distribution of respondents by year/grade is shown in Table 4.1. Sophomore students (Year 2) accounted for the largest proportion (33.3%), followed by juniors (Year 3, 27.9%), seniors (Year 4, 18.3%), and top-up students (ZhuanShengBen, 20.5%). Overall, the distribution across year levels is relatively balanced, which facilitates subsequent comparative analyses.

Table 4.1
Year/Grade Distribution of Survey Respondents

Year/Grade	Frequency (N)	Percentage (%)
Sophomore (Year 2)	202	33.3
Junior (Year 3)	169	27.9
Senior (Year 4)	111	18.3
Top-up (ZhuanShengBen)	124	20.5

Total	606	100.0

Q2. Major/Discipline of Respondents

The distribution of respondents by major/discipline is presented in Table 4.2. The majority of students were from engineering disciplines (74.9%), followed by management (23.3%), while students from other disciplines accounted for a small proportion (1.8%). This distribution adequately represents students from different academic backgrounds.

Table 4.2
Distribution of Respondents by Major/Discipline

Major/Discipline	**Frequency (N)**	**Percentage (%)**
Engineering	454	74.9
Management	141	23.3
Others	11	1.8
Total	606	100.0

Q3. Gender of Respondents

The gender distribution of respondents is shown in Table 4.3. Male students accounted for 56.9% of the sample, while female students accounted for 43.1%, indicating a relatively balanced gender distribution.

Table 4.3
Gender Distribution of Survey Respondents

Gender	**Frequency (N)**	**Percentage (%)**
Male	345	56.9
Female	261	43.1
Total	606	100.0

Q4. Final Exam Grade Distribution in Linear Algebra or Advanced Mathematics

The final exam grades in Linear Algebra or Advanced Mathematics were used as an important grouping variable in this study. As shown in Table 4.4, students with “Excellent” and “Good” grades accounted for 55.0% of the sample, indicating that more than half of the students performed at a relatively high level. Students with “Average” grades made up 22.3%, representing a moderate performance group. Those with “Pass” or “Fail” grades comprised 22.8% of the sample, providing a sufficient low-performance group for comparative analyses. Overall, the grade distribution covers high, medium, and low achievement levels, making it appropriate and reasonable to use as a categorical variable for further statistical analysis.

Table 4.4
Distribution of Final Exam Grades in Linear Algebra or Advanced Mathematics

Grade	Frequency (N)	Percentage (%)
Excellent	132	21.8
Good	201	33.2
Average	135	22.3
Pass	77	12.7
Fail	61	10.1
Total	606	100.0

Q5. Students' Perceived Difficulty in Learning Linear Algebra

Students were asked to evaluate the difficulty of learning Linear Algebra. The results, summarised in Table 4.5, indicate that a majority of students (50.2%) perceive Linear Algebra as "somewhat difficult," while 26.4% reported it as "average." Only a small proportion of students considered the subject "relatively easy" (12.5%) or "very easy" (3.5%), and 7.4% rated it as "very difficult." These findings suggest that most students encounter moderate challenges in learning Linear Algebra, highlighting the need for targeted learning support and instructional strategies to facilitate understanding of complex concepts.

Table 4.5
Perceived Difficulty in Learning Linear Algebra

Perceived Difficulty	**Frequency (N)**	**Percentage (%)**
Very Difficult	45	7.4
Somewhat Difficult	304	50.2
Average	160	26.4
Relatively Easy	76	12.5
Very Easy	21	3.5
Total	606	100.0

Q6. Use of AI Tools for Learning

Students were asked about their experience using AI tools to support learning. The results, summarised in Table 4.6, indicate that AI-assisted learning is widely adopted among the sampled students. Nearly 95% of respondents reported having used AI tools, with 45.7% using them frequently (at least twice a week) and 49.2% using them occasionally (once a week or less). Only a small proportion of students had either heard of but never used AI tools (4.1%) or had never heard of them (1.0%). These findings suggest that AI-based learning support has become an integral part of students' study practices in Linear Algebra and related disciplines.

Table 4.6
Frequency of AI Tool Usage in Learning

Usage Frequency	Frequency (N)	Percentage (%)
Frequent (at least twice a week)	277	45.7
Occasional (once a week or less)	298	49.2
Heard of but never used	25	4.1
Never heard of	6	1.0
Total	606	100.0

Q7. Preferred Learning Resources for Linear Algebra

The survey asked students to indicate their preferred learning resources for assisting with Linear Algebra study. The results are summarised in Table 4.7. The highest selection frequencies were observed for teacher videos (72.1%), graded exercises (56.9%), and animated demonstrations/concept visualizations (52.3%), suggesting that students tend to favor intuitive explanations and structured practice to support their learning. Other resources, including knowledge maps and personalized learning tools (42.1%), summary notes (36.3%), AI-assisted Q&A or intelligent feedback (33.8%), and peer discussion/group work (33.7%), were also commonly selected, highlighting the importance of diversified learning approaches in facilitating students' understanding and engagement.

Table 4.7
Students' Preferred Learning Resources for Linear Algebra

Learning Resource	Frequency (N)	Percentage (%)
A. Teacher videos (course recordings, lecture videos)	437	72.1
B. Animated demonstrations/concept visualization (e.g., dynamic matrix operation demonstrations)	317	52.3
C. Graded exercises (basic, intermediate, advanced)	345	56.9
D. Knowledge maps and personalized resources (e.g., concept maps, recommended learning paths)	255	42.1
E. Task-driven learning (e.g., case analysis)	181	29.9
F. Peer discussion / group work	204	33.7
G. Summary notes (teacher handouts / student notes)	220	36.3
H. Intelligent Q&A (AI-assisted answers, online platforms providing immediate feedback)	205	33.8
I. Others (please specify)	2	0.3
Total responses	2166	357.4

Q8. Tools or Platforms Commonly Used for Learning Linear Algebra

Students were asked to indicate which tools or platforms they primarily use to study Linear

Algebra and to rank them by frequency or preference. The results are summarised in Table 4.8. The most frequently used resources were Bilibili (video platforms, e.g., lecture recordings or open courses) (69.6%), Chaoxing Fanya Teaching Platform (57.4%), and teacher explanations or course materials (38.8%), indicating that online videos and teaching platforms remain the primary channels for learning. Other tools, such as printed textbooks (36.0%), generative AI tools (23.1%), and MOOC platforms (20.6%), were also utilized by a portion of students. This demonstrates that learners adopt multi-channel, multi-method strategies, with digital resources playing a particularly prominent role in supporting learning.

Table 4.8
Tools and Platforms Used by Students for Learning Linear Algebra

Tool/Platform	**Frequency (N)**	**Percentage (%)**
A. Chaoxing Fanya Teaching Platform	348	57.4
B. Rain Classroom (YuClass)	111	18.3
C. MOOC Platforms	125	20.6
D. Bilibili (video platforms, e.g., lecture recordings or open courses)	422	69.6
E. WeChat public accounts / resource groups	114	18.8
F. Math software (e.g., MATLAB/Maple/Python/R)	82	13.5
G. Generative AI tools (e.g., ChatGPT, for Q&A or content generation)	140	23.1
H. Teacher explanations or course materials	235	38.8
I. Printed textbooks	218	36.0
J. Knowledge maps	81	13.4
K. Peer discussions / group work	106	17.5
L. Classroom interactions	111	18.3
M. Others (please specify)	2	0.3
Total responses	2095	345.7

Q9. Descriptive Statistics of Questionnaire Modules

The descriptive statistics for each questionnaire module are presented in Table 4.9. The results include the number of items, mean, standard deviation, skewness, and kurtosis for each module. Overall, skewness and kurtosis values are close to 0, indicating that the data distributions are approximately normal, which is suitable for subsequent statistical analyses.

Table 4.9
Descriptive Statistics of Questionnaire Modules

Module	Number of Items	Mean	Standard Deviation (SD)	Skewness	Kurtosis
Module1: Learning Motivation and Interest	5	3.69	0.648	-0.536	0.149
Module2: Self-efficacy and Learning Strategies	5	3.58	0.704	-0.377	-0.676
Module3: Learning Platforms and Personalized Support	5	3.81	0.553	-0.195	-0.568
Module4: Higher-order Thinking Skills	8	3.36	0.699	-0.378	-0.064
Module5: Learning Resources and Knowledge Organization	6	3.78	0.739	-0.327	-1.091
Module6: Teacher Guidance and Support	5	3.94	0.625	-0.435	-0.777
Module7: Learning Resources and Collaboration	4	3.67	0.649	-0.107	-1.066

Summary of Student Questionnaire Data Analysis

A total of 606 valid questionnaires were collected in this study, providing data on students' learning motivation, self-efficacy, learning platform support, higher-order thinking skills, learning resources, teacher guidance, and collaborative learning across seven modules. The overall questionnaire demonstrated a high degree of structural validity, with a KMO value of 0.954 and a significant Bartlett's test of sphericity ($p < 0.001$). Reliability analysis showed that Cronbach's α coefficients for all modules exceeded 0.706, indicating that the questionnaire was well-structured and the scales exhibited good internal consistency and stability.

Regarding students' current learning status, approximately half of the respondents reported that learning Linear Algebra was "somewhat difficult," while only around 16% found it relatively easy, suggesting that most students still face challenges in the learning process. Furthermore, about 95% of students had experience using AI-assisted learning tools, with 45.7% classified as frequent users, indicating that intelligent learning tools are widely adopted among students. Preferred learning resources included teacher-recorded videos, graded exercises, and animated visual materials, highlighting the importance of intuitive explanations and stepwise practice for enhancing comprehension and learning engagement. In terms of learning channels, online video platforms (e.g., Bilibili) and teaching platforms (e.g., Chaoxing Fanya) were the primary sources, demonstrating the significant role of digital resources in learning.

The average scores across modules ranged from 3.36 to 3.94, reflecting an overall medium-to-high level. The modules "Teacher Guidance and Personalized Support" (M = 3.94) and "Learning Platform and Personalized Support" (M = 3.81) scored relatively high, indicating that students highly valued teacher guidance and platform feedback. Conversely, the "Higher-Order Thinking Skills" module received the lowest score (M = 3.36), suggesting that students still face challenges in abstract reasoning, knowledge transfer, and creative application, and thus require further training and support.

Overall, students generally exhibited relatively positive learning motivation and medium-to-high self-efficacy. They expressed high expectations for knowledge graphs, personalized platforms, and teacher guidance, while showing room for improvement in higher-order thinking skills and autonomous learning strategies. Therefore, instructional design should emphasize cognitive skill development, learning strategy guidance, and provision of personalized resources to facilitate the transformation from knowledge acquisition to competency development. The questionnaire results also highlighted three primary needs in current Linear Algebra learning: personalized learning pathways, higher-order thinking cultivation, and integration of digital and intelligent resources, providing empirical evidence and design references for constructing a knowledge-graph-based PLM.

Conclusion

This study adopts a mixed research design combining semi-structured interviews with teachers and questionnaires distributed to students to conduct a comprehensive demand analysis on the current teaching and learning status of Linear Algebra. A total of 12 frontline teachers and teaching administrators were interviewed, and 606 valid student questionnaires were collected. Through systematic analysis of qualitative and quantitative data, this study clarifies the current situation and existing problems in Linear Algebra teaching, and systematically sorts out the core demands of both teachers and students, which lays a solid empirical foundation for the subsequent construction of a knowledge graph-based personalized learning model oriented to the cultivation of higher-order thinking skills.

Core Research Findings and Demand Summary

Based on the integrated analysis of interview and questionnaire results, the core demands for Linear Algebra teaching and learning are summarized into three aspects as follows.

Teaching Implementation Demands

From the perspective of teachers, the core teaching demands are mainly reflected in the following aspects. Firstly, there is a demand for structured knowledge organization tools. Teachers generally hold that dividing curriculum content into core knowledge points and sorting out their logical correlations serve as the basis of personalized teaching, and professional knowledge graph construction tools are required to assist teaching design. Secondly, effective differentiated teaching strategies are urgently needed. Teachers encounter great difficulties in implementing personalized teaching for students with different academic foundations and disciplinary backgrounds, and expect practical group teaching methods and hierarchical task design schemes. Thirdly, abundant teaching resources for higher-order thinking tasks are required. Teachers need more discipline-specific real cases and inquiry-based task designs to guide students to shift from rote memorization and mechanical calculation to the cultivation of analytical, evaluative and creative competencies. Fourthly, intelligent teaching management support is expected. Teachers hope that teaching platforms can provide functions such as learning progress tracking, knowledge gap diagnosis and personalized resource recommendation to reduce the workload of manual teaching management.

Students' Learning Demands

First, students have a strong demand for intuitive and visualized learning resources. The survey reveals that 50.2% of students consider Linear Algebra a relatively difficult subject.

Their most preferred learning resources are teacher-recorded videos (72.1%), graded exercises (56.9%), and animation demonstrations & conceptual visualization materials (52.3%), indicating that abstract concepts need to be presented in more intuitive forms.

Second, students are in urgent need of personalized learning support. They expect to obtain customized learning paths and task recommendations tailored to their own mathematical foundations, learning paces and disciplinary characteristics. In particular, students with weak academic foundations require targeted remedial teaching.

Third, the training of higher-order thinking skills needs to be strengthened urgently. Among all questionnaire dimensions, the dimension of higher-order thinking skills scores the lowest (M=3.36), which reflects that most students have difficulties in abstract reasoning, knowledge transfer and innovative application, and more task-driven and inquiry-based learning activities are in great need.

Fourth, students require continuous emotional support and diversified learning channels. Approximately 95% of students have used AI-assisted learning tools. Meanwhile, they attach great importance to peer discussions, teacher-student interaction and timely feedback, hoping to relieve learning anxiety and improve learning motivation through various supportive mechanisms.

Model Construction Demands

In combination with the demands of teachers and students, the personalized learning model based on knowledge graph should possess the following core functions:

Knowledge graph visualization function: Clearly display the hierarchical relationships and logical connections between knowledge points, and support dynamic demonstration of abstract concepts.

Personalized learning path recommendation function: Generate customized learning paths based on student portraits and dynamically adjust them according to learning progress.

Hierarchical task design function: Provide basic, intermediate and advanced tasks matching students' learning skills, with a focus on cultivating higher-order thinking skills.

Multi-source learning resource integration function: Integrate various resources including teacher videos, animation demonstrations, graded exercises and AI Q&A to meet diversified learning needs.

Data-driven learning analysis function: Real-timely track students' learning behaviors, diagnose knowledge loopholes, and provide timely feedback and intervention.

Future Research Prospects

Future research will focus on the following directions. First, complete the design and development of the knowledge graph-based personalized learning model in accordance with the demands identified in this study. Second, carry out teaching experiments to verify the

effectiveness of the proposed model in improving students' learning outcomes of Linear Algebra and their higher-order thinking skills.

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