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Multimodal Learning Interaction in Multimedia Laboratory Environments: An Empirical Framework for Infrastructure Development

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Abstract

Multimedia-supported laboratory environments play an important role in enhancing learning engagement, conceptual understanding, and practical competence in higher education. However, limited empirical evidence exists regarding the relative contributions of the visual, auditory, and kinesthetic interaction dimensions to laboratory learning effectiveness. This study aimed to develop an empirical multimodal interaction framework for multimedia laboratory infrastructure development by examining the influence of these three dimensions on perceived learning effectiveness. A mixed-methods sequential explanatory design was employed. Quantitative data were collected from 101 university students enrolled in PTI Practicum, PTI Non-Practicum, and BK courses. Multiple regression analysis was conducted using responses from 58 students with direct laboratory practicum experience. Qualitative support was obtained through expert validation involving 14 lecturers. The data were analyzed using descriptive statistics, one-way ANOVA, Tukey's post hoc test, multiple linear regression, and expert triangulation. The descriptive analysis revealed that the kinesthetic dimension had the highest mean score, indicating a stronger preference for hands-on and experiential learning activities. However, the regression analysis demonstrated that the auditory dimension made the strongest contribution to perceived laboratory learning effectiveness, followed by the visual and kinesthetic dimensions. The regression model explained 64.8% of the variance in perceived learning effectiveness, indicating substantial explanatory power. The standardized regression coefficients were subsequently normalized and translated into infrastructure development priorities, forming the basis of the proposed empirical framework. Lecturer validation further emphasized the importance of experiential learning and practical engagement in laboratory environments, while highlighting the complementary roles of instructional communication and multimedia support in enhancing learning effectiveness. These findings suggest that effective multimedia laboratory environments should integrate instructional communication, multimedia visualization, and experiential learning facilities in a balanced manner, recognizing their complementary roles within a multimodal learning ecosystem. This study contributes an empirical framework to support adaptive multimedia laboratory infrastructure development and instructional design in higher education. In practice, the proposed framework may assist laboratory managers and higher education institutions in prioritizing instructional communication, multimedia visualization, and experiential learning facilities according to empirically identified learning interaction needs.

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INTRODUCTION

Multimedia integration in higher education enhances conceptual understanding, student engagement, and learning outcomes (Staneviciene & Žekienė, 2025). By facilitating active participation, gamification, and collaboration, multimedia environments offer alternatives to traditional didactic methods (Adeyele, 2024; Heliawati et al., 2022). These tools, through the integration of visual, auditory, and interactive components, support learning engagement and conceptual understanding across diverse student populations (Indriati et al., 2024; Patanduk et al., 2023; Wu, 2024).

However, the effectiveness of multimedia-supported learning environments depends not only on technology accessibility but also on pedagogical alignment with diverse tendencies in multimodal learning interactions. Despite the widespread availability of hardware, institutions often struggle to balance visual, auditory, and kinesthetic instructional interactions in learning activities (Chaw & Tang, 2023). Supporting these multimodal interaction tendencies is therefore considered important for improving learning engagement and instructional effectiveness (Hmedna et al., 2023).

Research highlights the need for adaptive instructional strategies to improve inclusivity and learning effectiveness within multimedia-supported educational environments (Septiani et al., 2024). Previous studies suggest that multimodal instructional approaches integrating Visual, Auditory, and Kinesthetic (VAK) interaction dimensions can support learning engagement more effectively than unimodal instructional environments, particularly for students with diverse learning needs (Gangadharan et al., 2025). Nevertheless, quantitative research examining the relative contributions of individual VAK dimensions toward perceived learning effectiveness, especially within specialized contexts such as multimedia computer laboratories, remains limited (Yaw Obeng, 2023).

To address this gap, this study develops an empirical regression model to examine the influence of the Visual, Auditory, and Kinesthetic dimensions on perceived laboratory learning effectiveness (Ristić et al., 2023). The resulting empirical evidence is expected to provide a foundation for developing multimedia laboratory infrastructure and instructional interaction design that accommodates diverse student learning needs. By examining the relative contribution of each multimodal learning dimension, this study aims to support evidence-based instructional strategies and multimedia laboratory infrastructure development (Abu-Issa et al., 2024).

Although the VAK framework has been widely applied in educational practice, contemporary educational research has questioned its interpretation as a deterministic classification of individual learning styles. Current perspectives argue that learners should not be categorized into fixed cognitive types because learning preferences are context-dependent and dynamic. Therefore, this study does not employ the VAK framework as a learner classification model. Instead, the Visual, Auditory, and Kinesthetic dimensions are operationalized as indicators of multimodal learning interactions within multimedia laboratory environments, enabling the analysis to focus on instructional interaction patterns rather than on individual learning-style categories.

The theoretical framework of this study is grounded in Mayer's Cognitive Theory of Multimedia Learning, which explains that learning effectiveness improves when verbal and visual information are integrated through multimedia representation (Mayer, 2024). Building on this perspective, Moreno and Mayer argue that interactive multimedia environments promote active cognitive engagement by enabling learners to organize and integrate information through multiple representational modes (Jacobs et al., 2024; Mayer, 2024). In addition, Kolb's Experiential Learning Theory emphasizes direct experience and experimentation as essential elements of meaningful laboratory learning (Srikasem et al., 2025). This perspective is further strengthened by Vygotsky's scaffolding theory, which highlights the importance of guided instructional interaction during experiential learning processes (Seery et al., 2024).

RESEARCH METHODS

A. Research Design

This study employs a mixed-methods sequential explanatory design to investigate the effectiveness of multimodal learning in multimedia-supported laboratory environments. By combining quantitative perception analysis with qualitative lecturer feedback, the research examines how multimodal learning interaction addresses differences in students' learning engagement and perceived conceptual understanding (Revano et al., 2024).

Drawing on Mayer's Cognitive Theory of Multimedia Learning, this study investigates how visual, auditory, and experiential learning support contribute to conceptual understanding and laboratory learning effectiveness (Mahmudah et al., 2026; Sinrang, 2025)

The research specifically analyzes the relationship between Visual, Auditory, and Kinesthetic learning dimensions and perceived laboratory learning effectiveness. The quantitative findings were subsequently strengthened through lecturer validation and expert triangulation to support the interpretation of multimodal learning interaction patterns within laboratory environments.

Furthermore, selected stages of the 4D framework were adapted as conceptual development guidelines to ensure that the proposed multimedia laboratory infrastructure framework was grounded in instructional design principles rather than merely technical implementation considerations.

The adapted 4D framework consisted of four stages: Define, Design, Develop, and Disseminate. The Define stage focused on identifying learning needs and challenges associated with multimedia-supported laboratory environments. Preliminary observations and a review of the literature were conducted to examine issues related to visual, auditory, and experiential learning support in laboratory-based activities.

The Design stage focused on developing the conceptual framework and research instruments based on the identified needs. The framework incorporated Visual, Auditory, and Kinesthetic dimensions as indicators of multimodal learning interaction. Questionnaires and validation instruments were also developed to assess perceived learning effectiveness and infrastructure support.

The Develop stage involved empirically examining the proposed framework through quantitative and qualitative analyses. Student responses were analyzed using descriptive statistics, one-way ANOVA, and multiple linear regression. Lecturer validation was conducted to enhance the interpretation and conceptual relevance of the findings.

Finally, the Disseminate stage focused on formulating and documenting the empirical framework to guide the development of multimedia laboratory infrastructure. The resulting framework is intended to support future instructional design and laboratory development initiatives in higher education.

B. Research Participants

The study was conducted within the Information Technology Education Program. A total of 101 students participated in the quantitative phase and were categorized into three groups: (1) PTI Practicum students, (2) PTI Non-Practicum students, and (3) BK students.

Purposive sampling was used to represent both intensive and non-intensive laboratory users. For the regression analysis, responses from 58 students with direct laboratory practicum experience were analyzed to ensure that evaluations of learning effectiveness were based on actual laboratory exposure. In addition, 14 lecturers participated in the expert validation phase based on their experience with laboratory-based and multimedia-supported learning.

Although the sample size for the regression analysis was relatively modest, it was considered adequate for exploratory multiple regression involving a limited number of predictors. Because the study examined only three independent variables, the available sample size was deemed sufficient to develop an exploratory empirical model. Nevertheless, future studies involving larger, multi-institutional samples are recommended to strengthen the external validity and generalizability of the proposed empirical framework.

C. Research Variables and Instruments

The study examined four primary constructs: (1) Visual, (2) Auditory, (3) Kinesthetic, and (4) Learning Effectiveness. The VAK dimensions were used as practical indicators of multimodal learning rather than as deterministic cognitive classifications. Data were collected through structured questionnaires using a five-point Likert scale.

Table 1. Research Variables and Indicators

Variable	Indicator	Example Questionnaire Item
Visual (V)	Multimedia display, diagrams, interface clarity, demonstrations	“I understand learning material more easily through visual representation.”
Auditory (A)	Verbal explanation, instructional communication, oral guidance	“Verbal explanation helps me understand laboratory procedures.”
Kinesthetic (K)	Hands-on practice, experimentation, direct interaction	“I learn more effectively through direct practice and experimentation.”
Learning Effectiveness (E)	Conceptual understanding, engagement, procedural comprehension	“Laboratory learning activities improve my understanding of the material.”

The student questionnaire comprised four dimensions: Visual, Auditory, Kinesthetic, and Learning Effectiveness, with five items for each dimension. Additional questions assessed students' preferences for multimodal learning configurations and their perceptions of the contribution of laboratory learning. Lecturer questionnaires were used to validate the instrument and estimate the proportional contributions of the VAK dimensions within multimedia laboratory environments.

D. Instrument Validation and Reliability

The instruments were reviewed by experts to ensure conceptual relevance and clarity. Reliability was assessed using Cronbach's alpha, and all constructs exceeded the acceptable threshold of 0.70, indicating good internal consistency. Before conducting the regression analysis, the assumptions of residual normality, absence of multicollinearity, and linearity were evaluated. Overall, the regression assumptions were considered acceptable for exploratory educational modeling.

Table 2. Instrument Reliability Results

Construct	Number of Items	Cronbach's Alpha
Visual	5	0.82
Auditory	5	0.79
Kinesthetic	5	0.85
Learning Effectiveness	5	0.81

E. Research Procedure

Data collection comprised three stages: a student survey, group classification, and lecturer validation and triangulation.

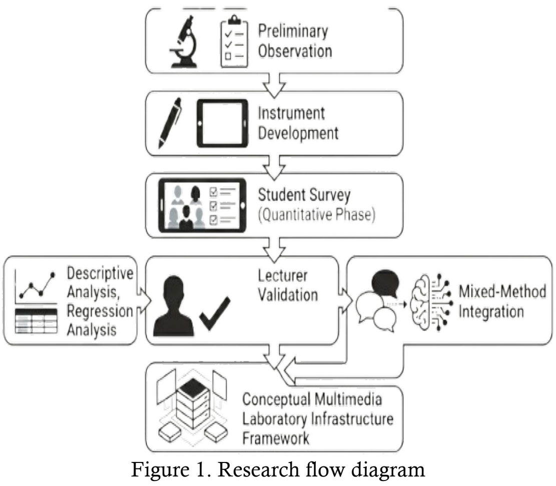

Figure 1. Research flow diagram

F. Data Analysis Techniques

Quantitative data were analyzed using SPSS through four procedures: (1) descriptive statistical analysis; (2) one-way ANOVA; (3) Tukey's HSD post hoc analysis; and (4) Multiple linear regression analysis. The regression model was specified in Formula 1.

$$E = aV + bA + cK \quad (1)$$

where:
E = perceived learning effectiveness,
V = visual dimension,
A = auditory dimension, and
K = kinesthetic dimension.

The regression coefficients were normalized to proportional contribution values to facilitate the interpretation of the multimedia laboratory infrastructure. Qualitative findings from lecturer validation and observations were integrated during the interpretation phase to provide a more comprehensive explanation of multimodal learning interaction patterns.

RESULT AND DISCUSSION

A. Instrument Reliability and Data Adequacy

The research instrument was developed based on four constructs: Visual, Auditory, Kinesthetic, and Perceived Laboratory Learning Effectiveness. Reliability testing using Cronbach's alpha demonstrated satisfactory internal consistency across all constructs, with coefficient values exceeding the minimum acceptable threshold of 0.70. These results indicate that the instrument was sufficiently reliable for exploratory educational research and suitable for subsequent statistical analyses.

A total of 101 students participated in the study. However, the regression analysis was conducted using responses from 58 students with direct laboratory practicum experience. This subset was selected to ensure that evaluations of laboratory learning effectiveness were based on actual laboratory exposure rather than hypothetical perceptions.

Table 3. Respondent Distribution

Respondent Group	Number of Respondents
PTI Practicum Students	58
PTI Non-Practicum Students	21
BK Students	22
Total Student Respondents	101
Lecturer Validators	14

B. Student Multimodal Learning Preferences

Descriptive analysis revealed differences across the three dimensions of multimodal learning. Table 4 presents descriptive statistics for the VAK Dimensions.

Table 4. Descriptive Statistics of VAK Dimensions

Component	Mean	Std. Deviation
Visual	18.24	4.02
Auditory	17.78	3.57
Kinesthetic	20.24	4.13

The kinesthetic dimension received the highest mean score, followed by the visual and auditory dimensions. These findings indicate that students value direct practical engagement and hands-on activities as important components of laboratory learning. The relatively high visual score also suggests that multimedia visualizations, demonstrations, clear interfaces, and graphical representations contribute positively to students' laboratory learning experiences.

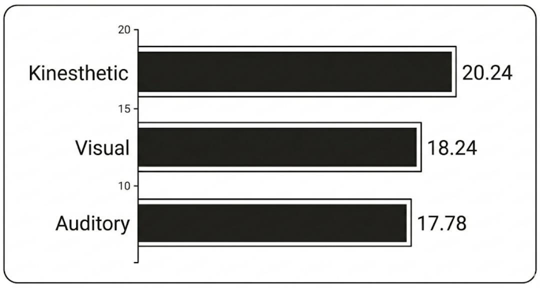

Figure 2. Mean comparison of VAK dimensions

Although the auditory dimension received the lowest descriptive score, verbal explanations and instructional communication remained important components of laboratory learning activities. From a pedagogical perspective, these findings are consistent with experiential learning principles, which emphasize active engagement and direct interaction as essential components of meaningful learning in practical environments.

C. Group Comparison Analysis

To examine whether laboratory exposure influenced students' multimodal learning tendencies, the respondents were categorized into three groups: PTI Practicum students, PTI Non-Practicum students, and BK students. The one-way ANOVA results revealed no statistically significant differences among the groups in the visual and auditory dimensions. However, a statistically significant difference was observed in the kinesthetic dimension.

Table 5. One-Way ANOVA Results

Dimension	F	Sig.
Visual	0.187	0.830
Auditory	1.284	0.282
Kinesthetic	6.437	0.002*

*Statistically significant at $p < 0.05$.

Post hoc Tukey analysis indicated that BK students had significantly lower kinesthetic tendencies than PTI Practicum students with laboratory experience. The mean kinesthetic scores were 20.87 for PTI Practicum students, 18.94 for PTI Non-Practicum students, and 16.72 for BK students.

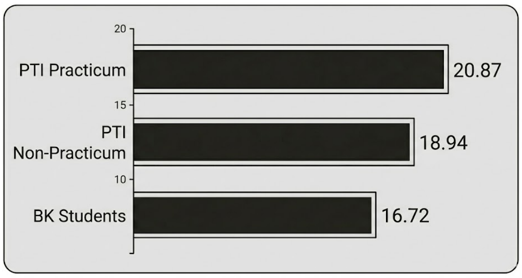

Figure 3. Kinesthetic mean scores by group

These findings suggest that laboratory exposure fosters the development of an experiential learning orientation. Students who regularly engage in laboratory activities appear to develop stronger preferences for practical exploration, experimentation, and direct interaction with learning resources.

D. Perceived Contribution of Laboratory Learning

Students were asked to evaluate the contribution of laboratory learning compared with conventional theoretical learning using a ten-point scale. The results indicated that laboratory learning was generally perceived as beneficial, with mean scores of 7.38 for PTI Practicum students, 7.71 for PTI Non-Practicum students, and 6.86 for BK students. Although descriptive differences were observed, the ANOVA results revealed no statistically significant differences among the groups. This finding suggests that students generally recognize the importance of laboratory-supported learning, regardless of their level of laboratory exposure.

E. Preference-Based VAK Configuration

Students were also asked to indicate their preferred multimodal learning configuration. Table 6 shows the preference-based VAK configuration.

Table 6. Preference-Based VAK Configuration

Configuration	Percentage
Visual-heavy	52.5%
Balanced Hybrid	19.8%
Kinesthetic-heavy	15.8%
Verbal-heavy	11.9%

The results indicated that 52.5% of students preferred visually oriented learning environments, 19.8% preferred balanced multimodal environments, 15.8% preferred kinesthetically oriented environments, and 11.9% preferred auditorily oriented environments. Interestingly, this finding contrasts with the descriptive VAK scores, in which the kinesthetic dimension had the highest mean. This discrepancy suggests that perceived learning preferences and actual learning behaviors may not necessarily reflect the same patterns of learning interaction. Although students may initially prefer visually rich learning environments, practical engagement appears to remain the dominant element during laboratory activities.

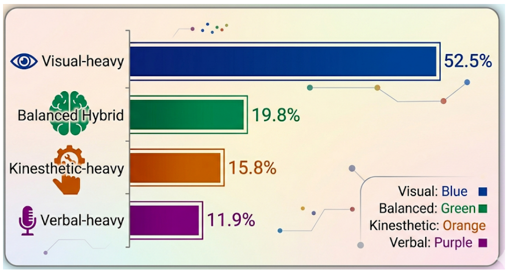

Figure 4. VAK preference distribution

F. Regression Analysis and Empirical Learning Model

Multiple linear regression analysis was conducted using responses from 58 students with direct experience in laboratory practicums. The conceptual model was formulated as Formula 2.

$$E = aV + bA + cK \tag{2}$$

Where E denotes perceived laboratory learning effectiveness, and V, A, and K represent the Visual, Auditory, and Kinesthetic dimensions, respectively. The empirical model derived from the analysis was:

$$\mathbf{E = 0.27V + 0.44A + 0.20K}$$

Table 7. Multiple Regression Analysis Results Model Summary

Indicator	Value
R	0.805
R^2	0.648
Adjusted R^2	0.628
F	33.133
Sig.	0.000

The regression model demonstrated strong explanatory capability with R = 0.805, R^2 = 0.648, and Adjusted R^2 = 0.628. These results indicate that the three multimodal dimensions explain approximately 64.8% of the variance in perceived laboratory learning effectiveness.

Table 8. Multiple Regression Analysis Results: Regression Coefficients

Variable	Beta	Sig.
Visual	0.269	0.040*
Auditory	0.436	0.000*
Kinesthetic	0.199	0.144

Among the predictors, the auditory dimension demonstrated the strongest standardized contribution, followed by the visual dimension. Although the kinesthetic dimension made a positive contribution, its partial effect was not statistically significant.

The absence of statistical significance should not be interpreted as evidence that experiential learning is unimportant in multimedia laboratory environments. Rather, it indicates that, after controlling for the visual and auditory dimensions, the unique predictive contribution of the kinesthetic dimension to perceived laboratory learning effectiveness could not be statistically distinguished within the present sample. Nevertheless, the descriptive analysis consistently showed that students expressed the strongest preference for kinesthetic engagement, while lecturer validation also emphasized experiential learning as a fundamental characteristic of laboratory-based education. Therefore, within the proposed empirical framework, the kinesthetic dimension should be interpreted as a complementary infrastructural component that supports practical learning experiences rather than as the primary statistical predictor of learning effectiveness.

The findings indicate that, although students favor hands-on interaction, instructional effectiveness in laboratory environments depends heavily on verbal explanation, procedural guidance, and instructional scaffolding. This pattern is consistent with Vygotsky's perspective that guided interaction plays an important role in supporting learning performance in experiential learning environments.

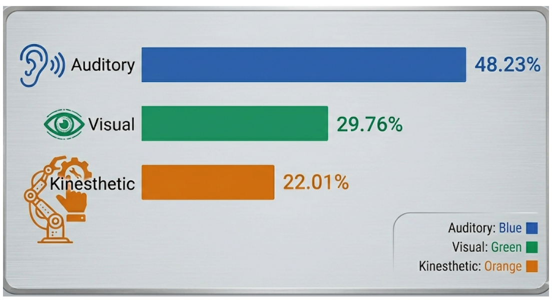

Figure 5. Infrastructure contribution framework

To support interpretation of the infrastructure, the standardized coefficients were converted to relative contribution values. The resulting proportions indicate that auditory support contributes 48.23%, visual support contributes 29.76%, and kinesthetic support contributes 22.01% to the proposed multimedia laboratory infrastructure framework.

These results suggest that effective laboratory environments should prioritize instructional communication systems while simultaneously integrating multimedia visualization and practical learning facilities.

G. Empirical Framework for Multimedia Laboratory Infrastructure Development

The regression analysis provides an empirical basis for translating multimodal learning interactions into priorities for multimedia laboratory infrastructure. To operationalize the statistical findings, the standardized regression coefficients were normalized and interpreted according to the relative contribution of each learning dimension to perceived laboratory learning effectiveness. These priorities were then aligned with the operational indicators measured in this study to develop an empirical infrastructure framework.

The auditory dimension made the greatest contribution, indicating that instructional communication should be the primary infrastructure priority. This includes facilities that support lecturer explanations, procedural guidance, collaborative interaction, and instructional scaffolding during laboratory activities. The visual dimension contributed 29.76%, emphasizing the importance of multimedia visualization through interactive displays, demonstrations, graphical representations, and clear interfaces. Although the kinesthetic dimension contributed 22.01%, the descriptive analysis revealed that students demonstrated the strongest tendency toward experiential learning, underscoring the continued importance of laboratory practice and hands-on learning facilities.

Accordingly, the proposed empirical framework recommends a balanced integration of instructional communication, multimedia visualization, and experiential learning facilities. Rather than prescribing specific technologies, the framework establishes evidence-based infrastructure priorities informed by the empirical contributions of each multimodal learning dimension. Consequently, it offers practical guidance for developing multimedia laboratory infrastructure in higher education.

H. Lecturer Validation and Expert Triangulation

Fourteen lecturers participated in the validation phase. The validation results are shown in Table 9.

Table 9. Lecturer Validation Results

Dimension	Mean	Std. Deviation
Visual	20.92	2.75
Auditory	22.92	2.36
Kinesthetic	23.23	1.88

The lecturers' responses yielded mean scores of 20.92 for the visual dimension, 22.92 for the auditory dimension, and 23.23 for the kinesthetic dimension. Table 10 shows the lecturer's contribution estimation.

Table 10. Lecturer Contribution Estimation

Component	Contribution
Visual	33.57%
Auditory	26.43%
Kinesthetic	40.00%

When asked to estimate the relative importance of each dimension, the lecturers assigned 40.00% to kinesthetic factors, 33.57% to visual factors, and 26.43% to auditory factors.

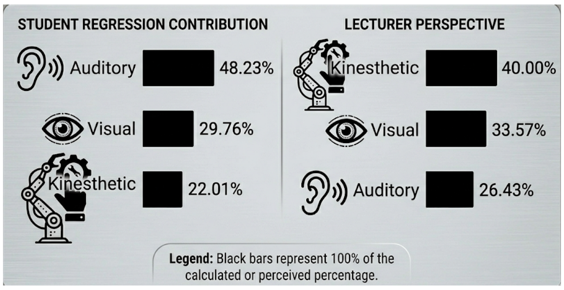

Figure 6. Student vs lecturer perspective comparison

The lecturers' perspectives reinforce the importance of experiential learning in laboratory environments. However, a notable divergence emerged between their perspectives and the students' regression results. Whereas students identified instructional communication as the strongest predictor of effectiveness, lecturers regarded direct practical engagement as the most important component of long-term learning.

This complementary perspective suggests that effective multimedia laboratory environments require both strong instructional support and meaningful opportunities for experiential learning.

Table 11. Empirical Infrastructure Development Framework

Empirical Dimension	**Relative Contribution**	**Infrastructure Priority**	**Infrastructure Function**
Auditory	48.23%	High	Supports instructional communication, procedural explanation, lecturer guidance, and collaborative discussion during laboratory learning.
Visual	29.76%	Medium	Supports conceptual understanding through multimedia visualization, interactive displays, demonstrations, and graphical representation.
Kinesthetic	22.01%	Medium	Supports experiential learning through practical workspaces, experimentation, and hands-on interaction with laboratory resources.

Note. Infrastructure priority levels were determined based on the normalized standardized regression coefficients obtained from the multiple regression analysis.

The proposed framework operationalizes the empirical findings by translating the relative contributions of the multimodal learning dimensions into infrastructure development priorities. Unlike a conceptual framework derived solely from theoretical considerations, this framework is grounded in the standardized regression coefficients obtained from the empirical analysis. Accordingly, it provides practical guidance for prioritizing instructional communication, multimedia visualization, and experiential learning facilities in the development of multimedia laboratory infrastructure.

The combined evidence from the descriptive findings, regression analysis, and lecturer validation demonstrates that statistical significance should not be interpreted independently of educational relevance. Although auditory interaction emerged as the strongest statistical predictor of perceived learning effectiveness, kinesthetic engagement remained pedagogically important because laboratory learning fundamentally depends on direct experimentation and practical experience. Accordingly, the proposed empirical framework integrates statistical evidence with pedagogical considerations to support the balanced development of multimedia laboratory infrastructure. This triangulated interpretation strengthens the framework's validity by incorporating statistical evidence, pedagogical expertise, and learner experience.

I. Discussion

The findings demonstrate that the effectiveness of multimedia laboratory learning is shaped by the interaction of visual, auditory, and kinesthetic dimensions rather than by a single dominant modality. Descriptive analysis revealed that students tend to favor kinesthetic engagement during laboratory activities. However, regression analysis identified auditory support as the strongest predictor of perceived laboratory learning effectiveness. This distinction suggests that, although students benefit from practical interaction, they also rely on verbal guidance and instructional communication to navigate laboratory activities successfully.

These findings are consistent with Mayer's Cognitive Theory of Multimedia Learning, which emphasizes the integration of multiple forms of information representation. Visual components support conceptual understanding, auditory components facilitate procedural comprehension, and kinesthetic activities promote experiential mastery.

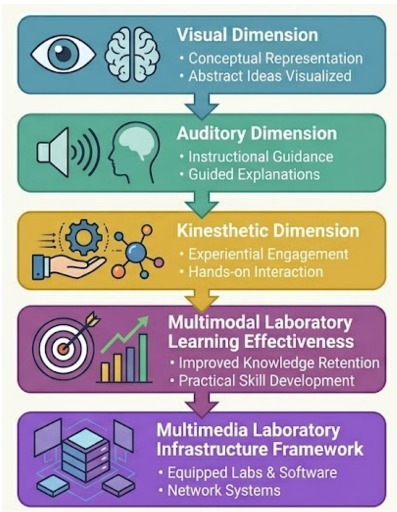

Figure 7. Empirical Framework for Multimedia Laboratory Infrastructure Development

Furthermore, the significant differences observed in the kinesthetic dimension across respondent groups indicate that laboratory exposure contributes to the development of experiential learning tendencies. Students who frequently participate in laboratory activities appear to develop stronger preferences for direct experimentation and practical exploration.

The triangulation results further support this interpretation. Students emphasized the importance of instructional communication during laboratory activities, whereas lecturers highlighted experiential mastery as a long-term educational objective. Together, these perspectives indicate that multimedia laboratory infrastructure should function as an adaptive pedagogical ecosystem rather than merely as a collection of technological resources.

Consequently, effective multimedia laboratory environments should integrate instructional communication systems, multimedia visualization facilities, experiential learning spaces, and collaborative learning opportunities in a balanced and complementary manner.

The empirical framework proposed in this study extends the regression findings beyond statistical interpretation by translating the relative contributions of the multimodal learning dimensions into infrastructure development priorities. The framework demonstrates that effective multimedia laboratory infrastructure should prioritize instructional communication while maintaining complementary investments in multimedia visualization and experiential learning facilities. Accordingly, laboratory infrastructure planning can be guided by empirical evidence rather than by technological availability alone, thereby strengthening the alignment between instructional requirements and infrastructure development.

CONCLUSION

This study investigated the contribution of visual, auditory, and kinesthetic dimensions to perceived learning effectiveness in multimedia-supported laboratory environments. The findings revealed that students showed the strongest descriptive tendency toward kinesthetic learning interaction, highlighting the importance of hands-on activities and experiential engagement in laboratory learning.

However, the regression analysis showed that the auditory dimension made the strongest contribution to perceived laboratory learning effectiveness, followed by the visual and kinesthetic dimensions. The empirical model explained 64.8% of the variance in perceived learning effectiveness and provided the basis for the proposed multimedia laboratory infrastructure framework.

These findings indicate that the development of multimedia laboratory infrastructure should prioritize instructional communication support, followed by multimedia visualization and experiential learning facilities, according to their relative contributions to perceived learning effectiveness. By translating the regression results into infrastructure development priorities, this study contributes an empirical framework that offers practical guidance for evidence-based multimedia laboratory planning in higher education.

The findings further indicate that effective multimedia laboratory environments should not focus exclusively on practical facilities but should also provide strong support for instructional communication and multimedia visualization. Integrating these dimensions creates a complementary multimodal learning ecosystem that supports conceptual understanding, procedural guidance, and experiential mastery.

The study also demonstrated that laboratory exposure contributes to the development of kinesthetic learning tendencies, while lecturer validation reinforced the importance of experiential learning as a core characteristic of laboratory-based education.

Overall, this study contributes an empirical multimodal interaction framework that may support the future development of multimedia laboratory infrastructure in higher education. Nevertheless, the study has several limitations. First, the empirical model was developed using respondents from a single study program at one higher education institution, which may limit the generalizability of the findings. Second, the regression analysis involved students with direct laboratory experience and should therefore be interpreted as an exploratory educational model rather than as a universally applicable infrastructure model. Future research should involve larger, multi-institutional samples; incorporate objective indicators of laboratory performance; and employ longitudinal evaluation designs to further validate, refine, and strengthen the generalizability of the proposed empirical framework.

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