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Cross-Disciplinary Perceptions of Cyber-Physical and Immersive Learning in Vocational Higher Education: Implications for SDG 4

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ABSTRACT

Objective: *To examine whether disciplinary affiliation differentiates vocational students' perceptions of Cyber-Physical Learning (CPL) and Immersive Learning (ILM) support for creative thinking and problem solving. It further considered the findings within a hardware–software convergence framework and their implications for competency-centered vocational education relevant to Sustainable Development Goal 4 (SDG 4).* ***Method:*** *A quantitative, comparative, cross-sectional survey was conducted using purposive sampling at Universitas Negeri Surabaya. The analysis included 222 valid respondents, comprising 109 Electrical Engineering and 113 Informatics Management students. A 31-item questionnaire using a five-point Likert scale assessed four perceived-support constructs: CPL for creative thinking (CPL-CT), CPL for problem solving (CPL-PS), ILM for creative thinking (ILM-CT), and ILM for problem solving (ILM-PS). Four independent-group Mann-Whitney U tests compared the two programs, supplemented by approximate standardized rank-test indicators derived from the reported Z statistics.* ***Results:*** *No statistically significant between-program differences were detected for CPL-CT ($p = .663$), CPL-PS ($p = .585$), ILM-CT ($p = .636$), or ILM_PS ($p = .689$). The derived standardized indicators were numerically small ($r = .027–.037$). These findings concern perceived learning support rather than demonstrated learning gains and do not establish practical equivalence or verify the proposed hardware–software convergence mechanism.* ***Novelty:*** *The study provides a cross-disciplinary assessment of four perceived learning affordances rather than comparing the superiority of particular technologies. The findings support consideration of competency-centered access to cyber-physical and immersive learning across vocational programs, with relevance to SDG 4. However, the study does not directly measure SDG attainment, actual skill development, or causal learning effects.*

INTRODUCTION

Digital transformation is changing both industrial work and the educational environments expected to prepare learners for it. Industry 4.0 combines networked devices, automation, computational systems, sensors, data processing, and digital interfaces in increasingly interdependent processes. Education 4.0 discussions consequently emphasize learning designs that integrate technological capability with adaptive problem solving rather than teaching distinct technologies in isolation (Chakraborty et al., 2023; de Souza & Debs, 2024; Mukul & Büyüközkan, 2023). Reviews of skills and higher-education responses to the Fourth Industrial Revolution similarly foreground the need for pedagogical flexibility and capacity to work across technological systems (Aboderin & Havenga, 2024; Teo et al., 2021). For vocational higher education, these developments raise a particular issue: technical specialization remains necessary, but the boundaries through which specializations are conventionally described may not correspond neatly to the socio-technical problems students will encounter.

The conventional distinction between hardware-oriented and software-oriented programs remains intuitively meaningful. Hardware-oriented education frequently stresses physical installation, equipment operation, electrical control, and observable

system behavior; software-oriented education more often foregrounds programming, information flows, digital services, and interfaces. Yet contemporary technical work regularly requires both dimensions. Literature on Industry 4.0 competence architecture, vocational work readiness, and technology-enabled learning factories underscores the integration of occupational, technological, and transversal competencies (Nurjanah et al., 2022; Perini et al., 2022; Roll & Ifenthaler, 2021). Human-centered learning-factory proposals extend that integration beyond technical operation toward adaptability and collaboration (Lagorio & Cimini, 2024). More recent vocational digital-skills discussions likewise frame technical expertise as an evolving combination rather than a fixed division between physical and computational work (Kurnia et al., 2026). Whether students' perceptions of learning environments continue to follow their nominal disciplinary affiliation is therefore an open empirical question.

Cyber-Physical Learning (CPL) offers one setting in which the question becomes visible. In the present study, CPL refers to the perceived pedagogical support associated with environments that integrate physical systems and digital functionality. Cyber-physical learning factories have been used to connect engineering design with operational systems, while interdisciplinary learning-factory designs combine physical prototyping, simulation, enterprise systems, and connected data (Chelini & Richert, 2023; Dobovičekt et al., 2025). Digital-twin reviews similarly describe interactions between real assets and computational representations (Kotecha et al., 2025). Importantly, the label CPL is not entirely uniform across scholarship: Sockalingam et al. (2025), for example, use it to describe synchronous participation by remote and in-person learners. These strands indicate overlapping physical–digital integration but should not be treated as operationally identical. The study therefore retains the meaning assigned to its own survey construct rather than assuming that all externally reported CPL implementations are interchangeable.

Immersive Learning (ILM) provides another setting for examining disciplinary boundaries. Immersive and extended-reality applications can represent technical situations through virtual objects, simulated operations, spatial visualization, or interactive scenarios. Reviews of immersive virtual reality describe varied learning purposes and design configurations rather than a single standard intervention (di Natale et al., 2020; Radianti et al., 2020; Stracke et al., 2025). Meta-analytic studies have reported positive effects on learning or engineering performance in specified settings; however, pooled estimates depend on interventions, outcomes, and participant characteristics. Coban et al. (2022) found a small overall immersive-virtual-reality effect (Hedges' g=0.38), while Li and Liang (2024) reported an overall virtual-laboratory effect of g=0.686 in engineering education. Yang et al. (2024) synthesized 37 studies and 72 effect sizes and found a moderate effect on practical skills (g=0.477). Such evidence establishes educational possibilities, not direct evidence about the perceptions measured in the present sample.

Immersive technologies are increasingly relevant beyond fields customarily associated with software. Engineering education reviews cover applications for visualization, safety, virtual practice, design understanding, and engagement across technical specializations (Suhail et al., 2024; Zontou et al., 2024). Systematic studies of augmented reality address collaborative higher-education activity (Upadhyay et al., 2024), vocational applications (Supriyanto et al., 2023), physics representations (Vidak et al., 2024), and chemical-engineering visualization (Rebello et al., 2024). This disciplinary breadth challenges the simple expectation that students whose programs emphasize digital interfaces must necessarily value immersive environments more strongly than

students engaged in equipment-based practice. It also raises the reciprocal question of whether software-oriented students necessarily perceive cyber-physical environments as less useful than their hardware-oriented peers.

The perceived support for creative thinking and problem solving provides a focused basis for these comparisons. Creative thinking concerns exploratory possibilities, alternative representations, and ideation; problem solving concerns identifying problems, evaluating options, and developing defensible responses. They are conceptually distinguishable even where their educational applications overlap. A review of virtual reality and university-student creativity identified applications across different learning fields (Yu & Wang, 2025), while research on presence and interactivity connects immersive experiences to learner agency and involvement (Petersen et al., 2022). Perceived usefulness and engagement in industrial-operations simulations may also vary with learner characteristics (Wong et al., 2023). Research on augmented reality and academic motivation cautions against reducing educational value to a technology label alone (Amores-Valencia et al., 2022). Broader evaluations of virtual-reality research emphasize that benefits are task-dependent (Bailenson et al., 2025). Accordingly, the present outcomes concern students' judgments of support for each competency, not observed improvements in cognitive performance.

A gap remains at the intersection of vocational disciplinary orientation, Cyber-Physical Learning (CPL), Immersive Learning (ILM), and perceived higher-order learning affordances. Existing scholarship has extensively examined immersive learning, technology-enhanced teaching, interdisciplinary learning factories, and the changing competencies associated with digitally transformed education. However, this literature does not establish whether membership in a conventionally hardware-oriented rather than software-oriented vocational program differentiates students' perceptions of how CPL and ILM support creative thinking and problem solving. Addressing this question is relevant to vocational higher education because contemporary technical learning increasingly combines physical, computational, and interactive environments. It is also relevant to SDG 4 insofar as competency-centered vocational education requires learning opportunities that can support students across disciplinary boundaries rather than assuming that particular technologies are inherently appropriate only for particular program labels. The present study therefore treats SDG 4 as an educational relevance framework rather than as an outcome variable; it does not directly measure progress toward SDG targets or indicators.

The empirical question is distinct from determining whether one learning environment outperforms another. It is also important to distinguish the absence of a statistically significant group difference from evidence that the groups are practically equivalent. Rank-based comparisons can reflect distributional characteristics beyond differences in central tendency (Hart, 2001), while evidence for negligible or practically unimportant differences requires an inferential framework specifically designed for that purpose rather than reliance on non-significant p values alone (Lakens, 2017; Lakens et al., 2020; Pawel et al., 2024). Accordingly, hardware–software convergence is used here as an interpretive framework for examining cross-disciplinary patterns, not as a mechanism directly measured by the survey. The findings may therefore be consistent or inconsistent with the convergence perspective, but they cannot independently verify that disciplinary boundaries have disappeared.

The objective of this study is to examine whether disciplinary affiliation is associated with different perceptions of learning support across four constructs: CPL for creative thinking (CPL-CT), CPL for problem solving (CPL-PS), ILM for creative thinking (ILM-

CT), and ILM for problem solving (ILM-PS). Two research questions guide the analysis. RQ1 asks whether Electrical Engineering and Informatics Management students differ in their perceptions of CPL support for creative thinking and problem solving. RQ2 asks whether the two groups differ in their perceptions of ILM support for these competencies. Electrical Engineering and Informatics Management are used as program-level proxies for hardware-oriented and software-oriented disciplinary orientations, respectively, rather than as direct measures of individual technological expertise.

The study contributes an independent-group comparison situated within a hardware-software convergence framework and an SDG 4-relevant vocational education context. Using a cross-sectional survey from one vocational faculty, it reports program-level descriptive scores and four Mann-Whitney U comparisons. The analysis does not compare CPL with ILM within respondents, assess actual creative-thinking or problem-solving performance, estimate causal effects, or test practical equivalence between the groups. Its contribution is therefore deliberately bounded: it evaluates whether formal disciplinary affiliation remains statistically informative for students' perceived support from technology-enhanced learning environments and considers what the observed pattern may imply for competency-centered vocational curriculum planning.

LITERATURE REVIEW

Disciplinary orientation in vocational higher education

Disciplinary affiliation is an institutional marker that summarizes intended curricular emphases, not a direct measurement of every learner's competencies. For this study, Electrical Engineering serves as the hardware-oriented category and Informatics Management as the software-oriented category. This operational contrast is intelligible within the historical organization of applied technical programs, but it is necessarily simplified. In contemporary vocational work, electronics, control systems, coding, and information services increasingly intersect. Reviews of Industry 4.0 competencies and Education 4.0 place collaborative, analytical, and technological abilities in interconnected frameworks rather than strictly separated disciplinary silos (Chakraborty et al., 2023; Perini et al., 2022). Work-readiness literature similarly emphasizes the capacity to adjust to changing technological requirements (Kurnia et al., 2026; Nurjanah et al., 2022).

The theoretical issue is whether this curricular contrast continues to explain perceptions of emerging learning environments. Broad educational transformation reviews describe changes in what students are expected to know, how they practice, and what technology allows institutions to simulate or connect (Aboderin & Havenga, 2024; Mukul & Büyüközkan, 2023). Such changes provide a rationale for questioning established categories, but convergence at the system level does not guarantee identical experiences or preferences among individuals. Program membership is therefore used as a grouping proxy that can be examined statistically, not as a direct measure of each respondent's prior technological exposure or self-identified professional specialization.

Cyber-physical learning as a cross-disciplinary environment

Cyber-physical learning arrangements connect tangible processes with computational representation, control, or observation. Learning Factories 4.0 provide an example of practice-oriented education organized around modern industrial competencies (Roll & Ifenthaler, 2021). A cyber-physical learning factory may embed design problems in

connected industrial settings (Chelini & Richert, 2023), while interdisciplinary implementations integrate operational processes, digital systems, Internet of Things connectivity, and physical prototypes (Dobovičeк et al., 2025). Human-centered factory designs likewise recognize the need to develop competencies across process, technology, and collaboration (Lagorio & Cimini, 2024).

The educational significance of this integration need not be restricted to learners identified as hardware specialists. Software development and digital interface work require awareness of physical-world constraints, while electrical and automation tasks may depend on programming, data interpretation, and network functionality. Reviews of digital twins further illustrate the mutual dependence of physical systems and their digital representations (Kotecha et al., 2025). Nevertheless, the scholarly term "cyber-physical learning" includes distinct models, including hybrid teaching participation as discussed by Sockalingam et al. (2025). Consequently, the empirical construct in this study is interpreted specifically as perceived support from the cyber-physical learning context described in the survey, rather than as a uniform implementation of every model found in the literature.

Immersive learning across disciplinary contexts

Immersive learning includes virtual and augmented experiences that may make abstract structures, inaccessible processes, or hazardous tasks more available for practice. Reviews show considerable variation in immersion, interactivity, pedagogical design, and learning objectives (di Natale et al., 2020; Radianti et al., 2020; Stracke et al., 2025). An earlier meta-analysis of virtual-reality instruction identified educational benefits while also illustrating heterogeneity across settings (Merchant et al., 2014). More recent quantitative syntheses reported g=0.38 for immersive virtual reality across selected outcomes (Coban et al., 2022) and g=0.686 for engineering virtual laboratories (Li & Liang, 2024). These pooled estimates describe intervention research and cannot be transferred directly to self-reported perceptions in a cross-sectional survey.

Engineering-specific reviews describe immersive use in technical simulation, practice, collaboration, and visualization (Dunmoye et al., 2026; Muzata et al., 2024; Zontou et al., 2024). Augmented-reality reviews identify applications across engineering teaching and spatial or conceptual understanding (Rebello et al., 2024; Suhail et al., 2024; Vidak et al., 2024). Meta-analytic evidence concerning practical skills also suggests that outcomes depend on the discipline and instructional configuration (Yang et al., 2024; Yuan et al., 2025). This diversity supports a cross-disciplinary analysis, rather than an a priori assumption that software-oriented students are the uniquely relevant audience for ILM. It also requires care: the supplied study notes do not specify particular devices, levels of immersion, or exposure duration for respondents.

Creative thinking and problem solving as perceived affordances

A learning affordance is considered here as an opportunity that students believe an environment provides for a specified activity or competency. Creative thinking and problem solving are related but are not reducible to a single general outcome. Literature on immersive experiences addresses openness to exploration, spatial experimentation, and creative expression (Yu & Wang, 2025), as well as interactivity, interest, and learner agency (Petersen et al., 2022). Collaborative meaning-making research places importance on dialogue surrounding immersive experiences rather than the visual encounter alone (Silseth et al., 2024). Empirical work on perceived usefulness and

engagement suggests that students' assessments of virtual environments can vary according to experience and disposition (Wong et al., 2023).

These sources provide reasons why both technical groups might find technology-enhanced environments supportive. However, perceived support is an attitudinal judgment; it must remain separate from demonstrated performance. Studies of augmented reality describe motivation, interactivity, and cooperative learning as potential mediators of educational activity (Amores-Valencia et al., 2022; Upadhyay et al., 2024; Supriyanto et al., 2023). At the same time, research on the use of educational data and artificial intelligence highlights how learning claims can be overstated when technologies are discussed without attention to pedagogical processes and evaluation (Zawacki-Richter et al., 2019). This study therefore evaluates four perception constructs, not actual creativity products, troubleshooting accuracy, or competence gains.

Hardware–software convergence and the conceptual framework

The proposed framework links digital transformation to increasingly integrated physical and digital work processes, places the two study programs as the disciplinary grouping variable, and examines perceptions of CPL-CT, CPL-PS, ILM-CT, and ILM-PS. Interdisciplinary factory designs and cyber-physical learning settings offer concrete examples of technologies that cross traditional curricular boundaries (Chelini & Richert, 2023; Dobovičeк et al., 2025). Learning-design reviews further warn that digital transformation involves institutional and educational redesign rather than merely adding technological hardware (de Souza & Debs, 2024; Teo et al., 2021).

Two interpretations remain plausible in advance of the analysis. Disciplinary specialization could produce different expectations about the relevance of physical-digital integration and immersive representations; alternatively, overlapping technological practices could reduce the explanatory value of program labels. The empirical question is whether detectable differences emerge between groups on the four measured constructs. Even if tests are non-significant, they cannot establish that disciplinary boundaries have vanished. The framework is therefore an interpretive model whose central convergence mechanism is proposed rather than directly measured; the observations can be consistent or inconsistent with it but cannot independently verify that mechanism.

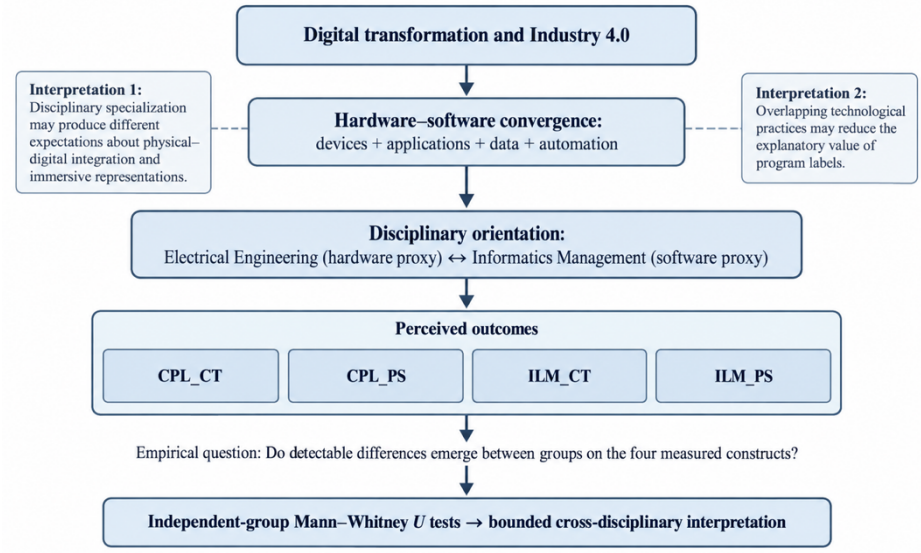


Figure 1. Conceptual model linking hardware-software convergence, disciplinary affiliation, and four perceived learning affordances.

RESEARCH METHOD

Research design and setting

The study employed a quantitative, comparative, cross-sectional survey design within the Faculty of Vocational Studies at State University of Surabaya. Its purpose was to examine independent-group differences in perceived learning support rather than to estimate causal impacts of an instructional intervention. Electrical Engineering was operationalized as the hardware-oriented group and Informatics Management as the software-oriented group. These classifications referred to academic program affiliation and did not constitute individual diagnostic assessments of students' hardware, software, or interdisciplinary proficiency. The unit of analysis was the individual survey respondent. The cross-sectional approach provided a single-time-point assessment, so changes over time, intervention effects, and differences in actual creative-thinking or problem-solving performance cannot be inferred.

This manuscript reuses the basic survey metadata from a related analysis of the same underlying dataset but addresses a different research question. Its inferential scope consists exclusively of four Mann-Whitney U comparisons between the two study programs. Paired, within-respondent comparisons of Cyber-Physical Learning and Immersive Learning, and interpretations based on those comparisons, are reserved for the related manuscript and excluded here. This separation preserves the present paper's specific focus on disciplinary orientation and reduces the potential for redundant presentation of results derived from a shared sample.

Participants and valid analytical cases

The original dataset contained 223 student responses. The source notes identify purposive sampling as the recruitment approach, reflecting a focus on vocational students associated with the two selected programs. However, the available research-note file does not provide recruitment dates, response rates, detailed eligibility thresholds, year of study, age, gender, or other demographic variables; such information is not reconstructed in this report. The distribution relevant for between-program tests was 109 Electrical Engineering students and 113 Informatics Management students. One original response had an unreadable or missing disciplinary grouping value. Accordingly, the independent-group analysis used 222 valid cases rather than 223.

Program affiliation was treated as a proxy for disciplinary orientation to test a conceptually motivated contrast. The design does not allow the classification to be generalized as if every Electrical Engineering participant worked primarily with hardware or every Informatics Management participant worked primarily with software. Differences in actual class exposure, digital confidence, and previous technical experience were not provided in the accessible dataset description. The findings are therefore interpreted as between-program comparisons at one institution, not as a population-level diagnostic contrast between all hardware-oriented and software-oriented learners.

Questionnaire and outcome operationalization

The survey used 31 questionnaire items rated on a five-point Likert scale, ranging from 1 to 5. Four construct scores were available for analysis: CPL-CT, perceived support of Cyber-Physical Learning for creative thinking; CPL-PS, perceived support of Cyber-Physical Learning for problem solving; ILM-CT, perceived support of Immersive Learning for creative thinking; and ILM-PS, perceived support of Immersive Learning

for problem solving. Each refers to students' judgments about the learning environment, not directly observed mastery of the named competency. Table 1 specifies the independent grouping variable and the four dependent measures.

The supplied research notes did not reproduce the wording of the 31 items, the allocation of items to constructs, reverse-scoring rules, missing-item thresholds, or the aggregation equations used to obtain construct scores. Although the group summaries indicate mean-type construct scores, these processing details should be confirmed against the original questionnaire and statistical syntax before submission. A full item list and scoring algorithm would materially improve measurement transparency. Empirical studies of immersive learning show that implementation features and perceived outcomes can differ across designs (Radianti et al., 2020; Wong et al., 2023); therefore, cross-study generalization based solely on broad CPL or ILM labels should be restrained.

Table 1. Study variables and operational definitions.

Role	Construct / variable	Operational meaning
Grouping variable	Disciplinary orientation	Electrical Engineering = hardware-oriented; Informatics Management = software-oriented
Outcome 1	CPL_CT	Perceived CPL support for creative thinking
Outcome 2	CPL_PS	Perceived CPL support for problem solving
Outcome 3	ILM_CT	Perceived ILM support for creative thinking
Outcome 4	ILM_PS	Perceived ILM support for problem solving

Data collection, ethics, and measurement quality

The available materials describe survey data from the designated vocational programs but do not provide the precise administration mode, fieldwork dates, consent procedure, or records of formal ethics review. No ethics approval number or waiver status can be responsibly inferred. These administrative details require verification from the researchers' original records before submission, alongside disclosure of the shared dataset if another manuscript based on these respondents has been published or submitted. The current draft intentionally does not substitute presumed procedural compliance for documentary confirmation.

The concept notes similarly indicate that Cronbach's alpha values for each of the four constructs, detailed item-validity statistics, and construct-validity outputs were not supplied with the drafting materials. Claims that reliability or validity reached specified numeric thresholds are therefore omitted. The need for appropriate measurement-quality reporting is especially important because coefficient alpha depends on assumptions and does not, by itself, establish dimensionality or validity (McNeish, 2018). Additional item-level evidence, when available, should be reported without altering the present between-program research question. Review literature likewise documents diverse constructs and measurement practices in immersive education, reinforcing the value of transparent instrument descriptions (Stracke et al., 2025).

Mann-Whitney U analysis and derived effect-size indicator

For RQ1, independent-group Mann-Whitney U comparisons were conducted for CPL-CT and CPL-PS. For RQ2, the same approach was applied separately to ILM-CT and ILM-PS. Each analysis contrasted the 109 valid Electrical Engineering responses with the 113 valid Informatics Management responses. The supplied statistical summaries include group means, mean ranks, U, standardized Z, and p values. Mann–Whitney U was used as a rank-based independent-sample procedure; however, the underlying

distribution shapes, tie corrections, confidence intervals, and exact software configuration were not supplied. Consequently, the test is reported as a comparison of distributions/ranks rather than asserted to be a pure comparison of medians. Hart (2001) identifies the importance of this interpretation when dispersion differs.

The source file did not present effect-size estimates. For interpretive context, the present draft calculates an approximate standardized rank-test indicator using $r=|Z|/\sqrt{N}$, where Z is the reported standardized test value and N=222 is the valid analytical sample. These derived indicators are reported explicitly as calculations from the supplied summaries, not as original study outputs. They do not replace estimates with confidence intervals, and their precision is limited by rounding of Z. The original results classified all four p values as non-significant. A conventional two-sided threshold of .05 is used only to summarize those classifications; the source does not document a prespecified alpha or multiplicity plan. Importantly, failure to reject a null hypothesis is not a test of practical equivalence or the absence of a meaningful effect (Lakens, 2017; Lakens et al., 2020; Pawel et al., 2024).

RESULTS AND DISCUSSION

Results

Analytical sample and reporting approach

Between-program analysis was based on 222 valid cases, comprising 109 students from Electrical Engineering and 113 students from Informatics Management. One of the 223 original respondents could not be assigned a readable disciplinary group and was not included in the between-group comparisons. Four independent tests were available: two for perceived Cyber-Physical Learning support and two for perceived Immersive Learning support. Table 2 reproduces the group means, mean ranks, U statistics, standardized Z statistics, and p values supplied in the source. The last column presents supplementary standardized r values computed from $|Z|/\sqrt{222}$; these values were not part of the source output.

Table 2. Independent-group Mann-Whitney comparisons by disciplinary orientation (EE, n = 109; IM, n = 113).

Outcome	Mean EE / IM	Mean rank EE / IM	U	Z	p	r†
CPL-CT	3.9644 / 3.9803	109.58 / 113.32	5948.500	−0.436	.663	.029
CPL-PS	4.0963 / 4.0450	113.91 / 109.22	5896.000	−0.546	.585	.037
ILM-CT	3.9869 / 3.9449	113.59 / 109.52	5930.500	−0.474	.636	.032
ILM-PS	3.9839 / 3.9671	113.26 / 109.83	5965.500	−0.400	.689	.027

Note. EE = Electrical Engineering; IM = Informatics Management.

All mean scores for the compared groups fell between 3.9449 and 4.0963 on the reported five-point scale. Thus, the observed mean ratings were numerically clustered toward the upper end of the response scale. The analysis nevertheless concerns differences between programs rather than a benchmark classification of the learning environments. Without respondent-level data, the observed means cannot support a distributional reconstruction, a bootstrap confidence interval, or a new significance test. No paired CPL-versus-ILM contrast is reported, because that inferential question belongs to the related study using this dataset.

The study was framed around two research questions rather than a comparison of instructional modalities. RQ1 addressed whether CPL perception scores varied by program for creative thinking and problem solving; RQ2 applied the same program contrast to ILM. Each construct was tested independently, with program orientation as the sole grouping label available in the research-note record. The numerical scores shown below therefore do not permit adjustment for potential differences in prior technological experience, program curricula, or characteristics such as age and academic level. This restricted specification is relevant when interpreting the scope of the observed tests.

Cross-disciplinary perceptions of cyber-physical learning

For perceived CPL support for creative thinking, Electrical Engineering students had a mean score of 3.9644, compared with 3.9803 for Informatics Management students. The descriptive difference, calculated as Electrical Engineering minus Informatics Management, was -0.0159 scale points. The rank ordering was consistent with these group means: the Electrical Engineering mean rank was 109.58, whereas the Informatics Management mean rank was 113.32. The Mann-Whitney test yielded U=5948.500, Z=-0.436, and p=.663. This p value was greater than .05, so the source classified the group comparison as not statistically significant. The computed standardized rank-test indicator was approximately r=.029. The observed ordering does not provide evidence of a reproducible advantage for one disciplinary group.

For perceived CPL support for problem solving, the descriptive ordering was reversed. The Electrical Engineering group mean was 4.0963 and the Informatics Management group mean was 4.0450, giving an arithmetic difference of +0.0513 scale points. Mean ranks were 113.91 and 109.22, respectively. The corresponding test produced U=5896.000, Z=-0.546, and p=.585, also classified as non-significant. The supplementary calculated indicator was r≈.037. Although the Electrical Engineering mean was somewhat higher on this construct, the available inferential result does not justify attributing a statistically reliable perceived CPL problem-solving advantage to program orientation.

The two CPL outcomes therefore answered RQ1 in the same inferential direction: neither comparison detected a statistically significant between-program difference. At a descriptive level, Informatics Management was marginally higher for CPL-CT, whereas Electrical Engineering was marginally higher for CPL-PS. This reversal illustrates why descriptive ranking alone cannot establish a generalized program effect. The presence of two outcomes is also important: creative thinking and problem solving are treated as separate perceived supports and are not collapsed into a single competency score. The results remain specific to their measurement instruments and to the independent-group analysis performed on the valid cases.

Prior investigations of learning factories and industrial education describe cross-domain technical processes that make the CPL constructs theoretically relevant to both programs (Chelini & Richert, 2023; Dobovičekt et al., 2025; Roll & Ifenthaler, 2021). These external studies serve as context only; they were not part of the statistical comparison and do not explain its observed p values. The group means, ranks, and test statistics establish the empirical result reported here, while the question of why students responded as they did is reserved for the Discussion section.

Within the CPL comparisons, the absolute differences in program means were 0.0159 for creative thinking and 0.0513 for problem solving. The difference in mean ranks was 3.74 rank units for CPL-CT and 4.69 rank units for CPL-PS in absolute terms. In both

outcomes, the reported standardized Z values were below 0.6 in absolute magnitude. These numerical descriptions are included to characterize the observed sample pattern; they do not identify an acceptable margin of educational equivalence. Because group-level standard deviations were not supplied, standardized mean differences and confidence intervals around the mean-score contrasts cannot be calculated reliably from the available record.

Cross-disciplinary perceptions of immersive learning

For perceived ILM support for creative thinking, the mean was 3.9869 in Electrical Engineering and 3.9449 in Informatics Management. The arithmetic between-group difference was +0.0420 scale points. Mean ranks were 113.59 and 109.52, respectively. The reported Mann-Whitney result was U=5930.500, Z=-0.474, and p=.636. The comparison was classified as not statistically significant, and the computed standardized rank-test indicator was r≈.032. Accordingly, the somewhat higher Electrical Engineering mean should be treated as a descriptive feature of this sample, not as evidence that immersive learning consistently provides greater creative-thinking support within hardware-oriented programs.

For perceived ILM support for problem solving, group means were likewise close: 3.9839 for Electrical Engineering and 3.9671 for Informatics Management. The descriptive difference was +0.0168 scale points. Mean ranks were 113.26 for Electrical Engineering and 109.83 for Informatics Management. The reported test yielded U=5965.500, Z=-0.400, and p=.689. The resulting comparison was non-significant; the derived effect-size indicator was approximately r=.027. Among the four reported tests, this outcome had the largest p value, although such ordering should not be taken as a quantitative measure of evidential strength for equivalence.

Both ILM outcomes thus addressed RQ2 without showing a statistically significant difference between the two study programs. Electrical Engineering obtained slightly higher descriptive means for both ILM-CT and ILM-PS, but neither contrast met the source's conventional significance interpretation. The mean-rank patterns were consistent with the same descriptive ordering. The results cannot identify which type of virtual, augmented, or simulated learning experience respondents had encountered, since device types, activity patterns, and duration of use were not specified in the source notes. Research on immersive learning identifies substantial instructional and implementation variability (Radianti et al., 2020; Stracke et al., 2025), but such variability was not measured as a moderator in this dataset.

Meta-analyses of virtual laboratories and practical-skills training report educational effects from defined interventions rather than discipline-based perceptions drawn from a survey (Li & Liang, 2024; Yang et al., 2024; Yuan et al., 2025). Therefore, their pooled outcomes should not be used as numerical comparators for the present Mann–Whitney statistics. The data here permit the narrower statement that neither of the two between-program differences in perceived ILM support was detected as statistically significant in the analyzed sample.

For the ILM outcomes, the absolute descriptive differences between group means were 0.0420 for creative thinking and 0.0168 for problem solving. The absolute mean-rank gaps were 4.07 and 3.43 rank units, respectively. Both rank contrasts pointed descriptively toward higher Electrical Engineering scores, but the standardized test statistics were only −0.474 and −0.400. These observations reinforce a limited descriptive reading: the group patterns were close in this analyzed set of respondents.

They do not show that an alternative measurement instrument, a different cohort, or a more tightly defined immersive activity would produce the same pattern.

Consolidated pattern and statistical boundaries

Across the four constructs, the reported p values were .663 (CPL-CT), .585 (CPL-PS), .636 (ILM-CT), and .689 (ILM-PS). All exceeded .05. Their computed standardized $|Z|/\sqrt{N}$ indicators were approximately .029, .037, .032, and .027, respectively. These supplementary values are numerically small as rank-test indicators but provide neither equivalence bounds nor confidence intervals for the population differences. The source supplied no raw scores with which to examine group dispersion, ceiling effects, missing questionnaire items, or the robustness of inferential conclusions under alternative models.

The substantive result is therefore the absence of statistically detectable differentiation by the two academic programs in this dataset, not the demonstration that students are identical or that disciplinary orientation lacks relevance in all circumstances. In particular, an inference about similar underlying distributions would require information on shape, precision, and a prespecified criterion for meaningful differences (Hart, 2001; Lakens, 2017). The present descriptive and inferential results are reported independently of the within-person CPL-versus-ILM comparison, which is intentionally excluded from this article.

The four outcomes are presented together because they were generated from one sample and share the same grouping structure. Separate p values must nevertheless retain their construct-specific meanings. A result for CPL-CT concerns perceived cyber-physical support for creative thinking and cannot substitute for CPL-PS, ILM-CT, or ILM-PS. Moreover, the study notes do not document an adjustment for multiple comparisons, so no unreported familywise procedure is attributed to the original analysis. At the same time, all four unadjusted p values already exceed .05; an adjustment cannot convert these findings into significant differences under conventional correction procedures.

Discussion

Cyber-physical learning beyond hardware-oriented programs

The absence of statistically significant between-program differences for CPL-CT and CPL-PS is important because CPL is sometimes intuitively associated with hardware-rich laboratory activity. In this sample, however, the students categorized as hardware-oriented did not report a statistically distinguishable level of perceived CPL support from those categorized as software-oriented. One possible explanation is that contemporary cyber-physical tasks require both tangible equipment and the computational systems used to monitor and control it. Learning-factory research increasingly organizes education around integrated design, connected operations, and digital systems rather than only conventional machinery (Chelini & Richert, 2023; Dobovičekt et al., 2025; Roll & Ifenthaler, 2021). This interpretation is consistent with the observed pattern but remains untested, since the survey did not directly measure actual interdisciplinary participation or technological exposure.

Cyber-physical environments can provide digital traces of physical events, and meaningful participation may depend on software interpretation as well as practical equipment use. Reviews of digital twins and industrial learning factories similarly describe learning activities built across representational and operational layers (Kotecha et al., 2025; Lagorio & Cimini, 2024). Yet the present study cannot establish which

components students considered when responding to CPL items. Its scope is the perception of support for creative thinking and problem solving, not verified engagement with individual sensors, cloud platforms, or physical prototypes. Consequently, the evidence challenges an automatic assumption of hardware-specific appeal without proving that software-oriented and hardware-oriented learners experience CPL in the same way.

Immersive learning beyond software-oriented programs

Neither immersive-learning construct exhibited statistically significant differentiation by study program. This result is pertinent to the expectation that software-oriented students, presumed more familiar with digital interfaces, would necessarily judge ILM more favorably. The observed descriptive means actually favored Electrical Engineering slightly on both immersive-learning outcomes, although these modest differences were non-significant. Immersive environments can support visual reasoning, safe representation of equipment behavior, and scenario-based exploration in disciplines that involve material systems. Reviews in engineering education document uses across a wide range of technical content (Muzata et al., 2024; Suhail et al., 2024; Zontou et al., 2024). Immersive affordances should therefore not be assumed to belong exclusively to software-centered programs.

At the same time, the term ILM encompasses more than one kind of instructional encounter. Literature distinguishes virtual and augmented reality, differing levels of interactivity and immersion, and varying collaborative or individual learning designs (Dunmoye et al., 2026; Radianti et al., 2020; Stracke et al., 2025). Empirical work also emphasizes that surrounding dialogue and activity design are integral to what learners make of immersive experiences (Silseth et al., 2024). Since the dataset description does not state which platforms or scenarios the students used, perceived similarity should not be attributed to an identical intervention. Task-specific benefits identified in broader VR research (Bailenson et al., 2025) offer a reason to investigate pedagogical design rather than treating the technology itself as a sufficient explanation.

Hardware–software convergence as a cautious interpretive lens

Together, the four comparisons are compatible with the central thesis that curricular boundaries between hardware and software may have reduced explanatory value where educational technology integrates physical and digital practices. Industry 4.0 competency literature situates contemporary work within interconnected systems and cross-cutting skills (Chakraborty et al., 2023; Perini et al., 2022). Education 4.0 and vocational-readiness scholarship likewise argues for learning environments that integrate technologies, pedagogy, and adaptive capacities (de Souza & Debs, 2024; Mukul & Büyüközkan, 2023; Nurjanah et al., 2022). The present study extends this conceptual discussion by directly testing four program-based perception contrasts rather than assuming that specializations predict preferences.

Nevertheless, convergence remains an interpretive construct and was not operationalized as an independent variable in the survey. The non-significant comparisons do not show that differences are absent, that group distributions are equivalent, or that any educational changes caused the patterns. A small Z-derived indicator is not a substitute for uncertainty quantification or a prespecified smallest effect of interest. Methodological scholarship on null results stresses the difference between insufficient evidence against a null and positive evidence for a sufficiently small effect (Lakens, 2017; Lakens et al., 2020; Pawel et al., 2024). Accordingly, “no

statistically significant disciplinary differentiation was detected" is a defensible empirical statement; claims of full hardware–software equivalence are not.

Implications for vocational curriculum and institutional design

One practical implication is that institutions need not allocate all cyber-physical opportunities to programs labeled hardware-oriented or all immersive opportunities to those labeled software-oriented. A competency-centered planning process can begin with the learning activity-creative exploration, systems diagnosis, simulation, design reasoning, or feedback interpretation and then select physical-digital, immersive, or blended resources accordingly. Reviews of augmented-reality collaboration and technical applications illustrate the breadth of activities that can be supported by properly designed environments (Rebello et al., 2024; Upadhyay et al., 2024; Vidak et al., 2024). Higher-education reviews also show that technological introduction requires pedagogical planning and instructional capability, not only investment in devices (Aboderin & Havenga, 2024; Teo et al., 2021).

These implications should be understood as proposals for curricular consideration, rather than as the measured outcomes of an intervention. The study contains no instructional-cost comparisons, faculty-capacity measures, performance indicators, or observations of how students interact with specific technologies. Work on VR engagement and augmented-reality motivation points to design and learner experience as consequential variables (Amores-Valencia et al., 2022; Wong et al., 2023), while a review of virtual and augmented reality with learning analytics stresses the diversity of stakeholders and evidence needs (Sakr & Abdullah, 2024), and research on education analytics reminds institutions that evaluation frameworks should connect technological provision to the learner activities actually observed (Zawacki-Richter et al., 2019). Future curriculum trials could therefore compare task-matched physical-digital and immersive activities using behavioral, performance, and qualitative measures across multiple programs.

Implication for SDG 4

The findings also have relevance to Sustainable Development Goal 4 (SDG 4) in the context of technology-enhanced vocational education. The absence of statistically significant differences between Electrical Engineering and Informatics Management students suggests that perceived support from cyber-physical and immersive learning environments is not necessarily confined to conventional hardware- or software-oriented program boundaries. This pattern provides a rationale for considering competency-centered access to technology-enhanced learning opportunities across vocational programs, particularly when learning activities are designed to support creative thinking, problem solving, technological adaptability, and engagement with integrated physical–digital systems. Such an approach is consistent with broader calls for vocational and higher education to respond to changing technological requirements through flexible, interdisciplinary, and pedagogically grounded learning environments (Aboderin & Havenga, 2024; Nurjanah et al., 2022; Teo et al., 2021). However, the present study did not measure SDG indicators, actual skill attainment, employability, or changes in learning performance. Therefore, the results should be interpreted as informing educational planning relevant to SDG 4 rather than as evidence that the implementation or achievement of SDG 4 has been demonstrated.

Contribution, limitations, and directions for further research

The study's principal empirical contribution is narrow but distinct: it provides four independent-group comparisons of perceived learning support across Electrical Engineering and Informatics Management students, covering two learning contexts and two competency dimensions. Its conceptual contribution is to interrogate disciplinary orientation as an explanatory category in increasingly integrated vocational systems. Unlike work that evaluates a particular immersive intervention or laboratory configuration, this analysis asks whether nominal disciplinary membership differentiates perceptions of technology-enhanced opportunities. The design also preserves a separation from the related article's paired CPL-versus-ILM comparisons. Transparency about shared data is important for readers and editors assessing the independence of research questions and inferential claims.

Interpretation remains constrained by a single institution, two programs, purposive recruitment, and one excluded grouping-variable case. Program affiliation is an imperfect surrogate for technical orientation. Outcomes were self-reported perceptions rather than observed creative products or problem-solving performance. The notes do not provide respondent demographics, test-distribution shapes, detailed item wordings, construct reliability and validity statistics, or confirmed survey and ethics procedures. Neither effect-size confidence intervals nor formal equivalence tests were available. Reviews of immersive education show extensive methodological diversity (Stracke et al., 2025; Yuan et al., 2025), making these omissions especially relevant for replication. Further work should include direct profiling of technological experience, transparent psychometrics, larger multi-institution samples, registered smallest effects of interest, and longitudinal or mixed-method designs that examine actual learning processes.

A productive extension would assess whether shared exposure to integrated laboratories, digital control systems, or simulation-based exercises moderates the relationship between program and perception. Another would examine whether curricular task type, prior programming experience, hands-on proficiency, and access to learning technologies are more informative predictors than formal program designation. These designs could test the proposed convergence mechanism directly rather than reading it into the absence of significant program differences. This would provide a stronger basis for claims about changing disciplinary boundaries and more actionable evidence for decisions regarding technology-enhanced vocational learning.

CONCLUSION

Fundamental Finding: This study found no statistically significant differences between Electrical Engineering and Informatics Management students in their perceptions of Cyber-Physical Learning (CPL) and Immersive Learning (ILM) support for creative thinking and problem solving. The independent-group analysis included 222 valid respondents, comprising 109 Electrical Engineering and 113 Informatics Management students. All four Mann-Whitney U comparisons were non-significant (p=.585, –.689), with small approximate standardized rank-test indicators derived from the reported Z statistics (r=.027, –.037). Thus, disciplinary affiliation did not statistically differentiate the four perceived learning affordances in this sample. These findings are compatible with hardware–software convergence as an interpretive perspective, but they neither verify the proposed convergence mechanism nor establish practical equivalence between the groups. **Implication:** The findings invite vocational institutions to reconsider allocating cyber-physical and immersive learning opportunities solely according to hardware-oriented or software-oriented program labels. Curriculum

planning may instead prioritize targeted competencies and learning activities, including creative exploration, systems diagnosis, simulation, and design reasoning, when selecting technological resources. Cross-program access to these environments therefore merits consideration without assuming that CPL is inherently more appropriate for Electrical Engineering or that ILM is inherently more appropriate for Informatics Management. These implications constitute proposals for instructional planning rather than demonstrated improvements in learning performance; their effectiveness requires evaluation through actual learning activities and outcomes. **Limitation:** Interpretation is constrained by purposive sampling from two programs at a single institution and a cross-sectional design that cannot establish causality or changes over time. Program affiliation served as an imperfect proxy for individual technological orientation, while the outcomes represented self-reported perceptions rather than demonstrated creative-thinking or problem-solving performance. Limited documentation of participant characteristics, technological exposure, questionnaire scoring, measurement quality, and survey procedures further restricts interpretation and replication. Additionally, the absence of effect-size confidence intervals and formal equivalence tests prevents the non-significant findings from being interpreted as evidence that educationally meaningful differences are absent. **Future Research:** Future investigations should involve larger, multi-institutional samples, provide transparent instrument validation, and directly assess students' programming experience, hands-on proficiency, technological access, and exposure to integrated learning environments. Longitudinal and mixed-method designs should connect perceived learning support with observed creative products, problem-solving performance, and learning processes. Prespecified smallest effects of interest, effect-size confidence intervals, and formal equivalence testing would enable more informative interpretation of small or non-significant differences. Directly examining whether shared technological experiences moderate the relationship between program affiliation and perceptions would test the proposed convergence mechanism, providing a stronger basis for determining whether actual learning experiences are more informative than disciplinary labels in technology-enhanced vocational education.

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AUTHOR CONTRIBUTIONS

Reza Rahmadian: Conceptualization, methodology, investigation, and writing-original draft preparation. **Ekohariadi:** Supervision, validation, and writing-review and editing. **Ratna Suhartini:** Methodology, formal analysis, and writing-review and editing. **Mafrur Udhif Nofaizzi:** Data curation, investigation, visualization, and writing-original draft preparation. All authors have read and approved the final version of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that no conflict of interest, either financial or personal in nature, exists that could have influenced the design, execution, interpretation, or reporting of

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ETHICAL COMPLIANCE STATEMENT

This manuscript adheres fully to the principles of research and publication ethics. The study was conducted with academic integrity, and all data reported herein were collected, processed, and presented accurately and transparently. No data were fabricated, falsified, or selectively reported.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

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