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Cognitive Load Architecture and Visual-Representational Competence in Plant Morphology Learning: A Multivariate Study of Pre-Service Biology Teachers

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Abstract

Plant morphology requires students to coordinate visual features, spatial relations, and biological terminology. This cross-sectional, correlational, multi-site secondary analysis examined whether metacognition and three operational dimensions of cognitive load were associated with representational and spatial abilities among pre-service biology teachers. The analysis used complete-case data from 280 Biology Education students in the fourth, sixth, and eighth semesters at participating higher-education sites across four Indonesian study regions. Participants had been selected under the parent project using a stratified sampling procedure targeting middle-to-late semesters, and the quantitative phase administered morphology-based performance tasks and self-report scales. Multivariate multiple regression showed a significant joint relationship between the predictors and the two outcomes, Pillai's V = .209, F (8, 550) = 8.03, p < .001. Extraneous load showed the strongest multivariate association, V = .098, F (2, 274) = 14.81, p < .001, while germane load was also significant, V = .043, F (2, 274) = 6.07, p = .003. In follow-up models, extraneous load was negatively and germane load positively associated with both outcomes. Within this sample, these two operational load dimensions showed more consistent relationships with visual-representational performance than intrinsic load; the correlational design does not establish causality.

Keywords: cognitive load, representational ability, spatial ability, plant morphology, pre-service biology teachers

1. Introduction

In a plant morphology class, students rarely work with words alone. They have to look closely at leaves, stems, roots, flowers, inflorescences, ovaries, and modified organs, then decide which structural features matter and how those features should be expressed in scientific language. This

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means that learning morphology is not simply a matter of memorizing terms. Students must compare specimens, recognize diagnostic characters, coordinate part-whole relations, and move between what they see and how the structure is represented in diagrams, sketches, labels, or descriptions. These demands are especially relevant for pre-service biology teachers, who will later be expected to explain the same structures to school students. Representational competence is therefore part of disciplinary understanding rather than an additional visual skill. Studies in science education show that learners who can read, interpret, construct, and evaluate representations are better able to organize information around meaningful biological features instead of relying mainly on surface appearance (Gardner et al., 2024; Knain et al., 2021; Newman et al., 2023; Tang et al., 2022).

Representational ability and spatial ability overlap, but they should not be treated as the same capacity. Representational ability concerns how students interpret and produce external forms such as diagrams, sketches, labels, and written descriptions (Gardner et al., 2024; Knain et al., 2021; Newman et al., 2023; Tang et al., 2022). Spatial ability is more concerned with mentally changing orientation, position, symmetry, or relationships among parts (Aspanani et al., 2023; Ho et al., 2022; Koh et al., 2023; Labranche et al., 2022; Sarilita et al., 2022; Wang & McWatt, 2023). This distinction becomes visible in morphology tasks. A student may correctly identify a structure in a familiar diagram but struggle when the same structure is shown from another angle; another may mentally recognize the structure but have difficulty explaining its diagnostic features in a scientific sketch. Research in anatomy has repeatedly shown that visuospatial ability contributes to learning complex structures and interacts with the way those structures are represented. Although plant morphology is not anatomy, similar demands arise when students distinguish leaf arrangements, interpret ovary position, recognize modified organs, or relate a two-dimensional image to a three-dimensional specimen. For that reason, this study considers representational and spatial performance together.

A second issue is how much cognitive effort is required while students are working with these visual and conceptual demands. Morphology asks learners to hold terminology, structural relations, and task goals in working memory while they inspect several features at once (Kastaun et al., 2021; Koć-Januchta et al., 2022). Some of this effort is unavoidable because the biological content itself is complex. Other effort, however, may come from the way information is presented. A crowded diagram, a label placed far from the structure it describes, inconsistent terminology, or unnecessary visual detail can make an already difficult task harder than it needs to be. Studies of multimedia and inquiry-based biology show that the design and usability of learning resources influence how cognitive resources are allocated (Kastaun et al., 2021; Koć-Januchta et al., 2022). Similar concerns have been reported in Indonesian studies of cell biology and plant tissue structure, particularly for extraneous cognitive load (Ermayanti et al., 2023; Juanengsih et al., 2021). Thus, difficulty in morphology may reflect not only what students have to learn, but also the cognitive conditions under which they try to learn it.

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The parent instrument used in this project distinguished three operational dimensions of cognitive load: intrinsic, extraneous, and germane load. Intrinsic load refers to perceived complexity arising from the material and the number of interacting elements that must be processed. Extraneous load represents cognitive demands that do not directly contribute to the intended learning, such as confusing organization or irrelevant information. Germane load, as measured in this instrument, reflects effort directed toward organizing and integrating information into a more coherent understanding. These dimensions are useful for morphology because they suggest different instructional problems. The inherent complexity of comparing organ structures cannot simply be removed. Unnecessary processing demands, in contrast, can be reduced. At the same time, productive effort may be needed when students compare several representations, connect a specimen with a diagram, or build a mental model of how parts are arranged.

Metacognition adds another layer to this process. Students need to notice when an identification is uncertain, check whether a diagram is consistent with the specimen in front of them, and reconsider an interpretation when the available evidence does not fit. In other words, knowing that one is unsure can be as important as knowing the correct term. Research with biology students has linked metacognitive monitoring, reflection, and study strategies to performance and error detection (Behrendt et al., 2024; Bernacki et al., 2023; Ewell et al., 2023; Knight et al., 2022). Metacognitive prompts have also been used to strengthen awareness and strategy use in biology and anatomy learning (Angell et al., 2024; Elsner & Großschedl, 2024; Ruth & Dzara, 2025). At the same time, metacognition is unlikely to operate independently of cognitive load. Monitoring, checking, and changing strategy all involve decisions about where attention and effort should be directed, and previous work has shown that cognitive-load patterns are intertwined with self-regulated learning behavior and metacognitive judgment (Wang et al., 2023).

Taken separately, the literature gives good reasons to expect representation, spatial processing, cognitive load, and metacognition to matter. The difficulty is that these strands of research have developed largely in parallel. Spatial studies are dominated by anatomy and three-dimensional learning; representational studies often focus on graphs, molecular diagrams, or science discourse; and cognitive-load studies commonly evaluate learning media rather than treating representational and spatial abilities as related outcomes. As a result, we still know relatively little about how these cognitive factors come together when pre-service biology teachers learn plant morphology. This gap is consequential for biology teacher education because future teachers must not only recognize plant structures but also translate them across specimens, diagrams, scientific descriptions, and changing viewpoints. Evidence about the cognitive conditions associated with these competences is therefore needed before instructional recommendations about visual materials or cognitive-load management are generalized to morphology learning.

We addressed this gap by re-examining the quantitative dataset from a different analytical perspective. The parent diagnostic analysis used misconception as the criterion variable and examined representational ability, metacognition, the three cognitive-load dimensions, and spatial ability as explanatory variables. The present article reuses the same participant dataset and some

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of the same measures but does not use misconception as an outcome. Instead, representational ability and spatial ability are specified as two related outcomes and are analyzed jointly in a multivariate model. Thus, the overlap lies in the participant dataset and predictor measures, whereas the research purpose, criterion variables, and inferential model differ from the parent diagnostic analysis. Accordingly, this study aimed to (1) examine the associations of metacognition and intrinsic, extraneous, and germane cognitive load with representational and spatial abilities in plant morphology; (2) determine which predictors show significant multivariate associations when both visual-representational outcomes are considered jointly; and (3) assess whether the outcome-specific associations remain after accounting for gender and semester.

2. Methods

2.1. Design, data provenance, and participants

The analysis reported here is a cross-sectional, correlational secondary analysis within the quantitative phase of a larger sequential explanatory mixed-methods project on plant-morphology learning. The parent diagnostic analysis focused on misconception as the criterion variable. In contrast, the present analysis asks a distinct question by treating representational ability and spatial ability as joint outcomes and metacognition plus the three operational cognitive-load dimensions as simultaneous explanatory predictors. No misconception prevalence, diagnostic-category comparison, or misconception-regression result is reproduced as an outcome in the present article. The word predictor is therefore used only in the statistical sense and should not be interpreted as evidence of temporal order or causation.

The analytic sample comprised 280 students enrolled in Biology Education programs at participating higher-education sites inherited from the parent project. To avoid mixing administrative levels, the manuscript refers consistently to four study regions: Aceh, Java, Kalimantan, and East Nusa Tenggara. These labels identify the geographic groupings represented in the de-identified dataset; they were not intended to be equivalent administrative units or a probability sample of Indonesian regions. Site inclusion in the parent project was intended to broaden academic and geographic variation rather than to estimate regional differences or represent every province or island. Parent documentation identifies a stratified random sampling procedure targeting students in middle-to-late semesters, but the de-identified analytic file available for this secondary analysis does not retain the institution-level sampling frame, stratum-specific selection probabilities, accreditation or curriculum descriptors, or the information needed to reconstruct why individual institutions within each study region were selected. Eighty-four participants were in the fourth semester (30.0%), 112 in the sixth semester (40.0%), and 84 in the eighth semester (30.0%); 198 were women (70.7%) and 82 were men (29.3%). All 280 cases contained complete values for the focal variables and were analyzed without imputation.

No new participant recruitment or data collection was undertaken for the present re-analysis; it used already-collected, de-identified records from the parent quantitative phase. Institution-specific

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recruitment logs, numbers invited or eligible, response-rate records, and institutional identifiers were not retained in the analytic file. Consequently, these quantities cannot be reconstructed here, no between-university comparison is made, and site-level clustering cannot be modeled. These limitations are reported explicitly because students from the same institution may share learning conditions that are not captured by the individual-level variables.

Table 1.
Participant characteristics

Characteristic	n	%
Fourth semester	84	30.0
Sixth semester	112	40.0
Eighth semester	84	30.0
Female	198	70.7
Male	82	29.3

2.2. Measures and instrument documentation

Representational ability was assessed through eight morphology-based tasks (R1-R8). The tasks covered leaf-part identification, simple versus compound leaves, venation and phyllotaxy, modified organs, inflorescence types, ovary position, and morphological description. The total score ranged from 0 to 24, with higher scores indicating stronger ability to interpret, discriminate, and express morphological information across representational forms.

Spatial ability was assessed with six morphology-based mental-rotation items (KS1-KS6). Each item was scored 1 for a correct response and 0 for an incorrect response, giving a total range from 0 to 6. The tasks were designed to capture mental manipulation of structural orientation and part-whole relations that are relevant when biological objects must be recognized across changes of perspective.

Metacognition was assessed using 12 statements rated from 1 (strongly inconsistent) to 5 (strongly consistent) and analyzed as the mean item response. Cognitive load was measured using 10 statements rated from 0 to 10. Three items represented intrinsic load (BK1-BK3), three represented extraneous load (BK4-BK6), and four represented germane load (BK7-BK10); each dimension was analyzed as an item mean. Instrument development in the parent project included expert content validation using Aiken's V, readability testing, a limited pilot, and internal-consistency evaluation using alpha/omega coefficients with .70 as the predefined adequacy criterion. The final field versions resulting from that process were used for the main data collection. However, the de-identified secondary-analysis file available for the present re-analysis does not contain the original validator ratings, pilot responses, or item-level validation output. Exact Aiken's V values, validator

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characteristics, and scale-specific alpha/omega coefficients were not available in the secondary-analysis file and therefore are not reported in the present article. This documentation gap is particularly relevant for the three- and four-item cognitive-load subscales; consequently, intrinsic, extraneous, and germane load are interpreted as operational dimensions of the parent instrument rather than as definitive estimates of latent constructs.

2.3. Data analysis

The analysis was carried out in four steps. We first summarized the two outcome variables and the four predictors using descriptive statistics. Pearson correlations were then examined to describe the bivariate relationships and to determine whether representational and spatial abilities were related enough to justify a joint analysis without being redundant measures. Next, we fitted a multivariate multiple linear regression model with representational ability and spatial ability as the outcome vector and metacognition, intrinsic load, extraneous load, and germane load as simultaneous predictors. Pillai's trace was used for the multivariate tests, followed by separate ordinary least-squares models for each outcome. We report unstandardized coefficients, standard errors, standardized beta coefficients, R-squared values, and p values. Finally, gender and semester dummy variables were added in a sensitivity analysis to check whether the main pattern was sensitive to the composition of the sample. Institutional identifiers were not available in the analytic file, so standard errors could not be adjusted for clustering by site and a site-level sensitivity analysis was not possible; the gender/semester sensitivity analysis does not substitute for modeling institutional clustering.

Model diagnostics did not indicate problematic multicollinearity; variance inflation factors for the four focal predictors ranged from 1.12 to 1.18. Residual diagnostics were acceptable for the follow-up models. For representational ability, the Shapiro-Wilk residual test was $p = .491$, the Breusch-Pagan test was $p = .365$, and Durbin-Watson was 2.24. For spatial ability, corresponding values were $p = .307$, $p = .838$, and 2.01. Statistical tests were two-tailed with alpha = .05. Analyses were conducted in Python using SciPy and statsmodels.

3. Result and Discussion

3.1. Descriptive profile and bivariate relationships

The mean representational-ability score was 15.66 (SD = 3.88) on the 0-24 scale, while the mean spatial-ability score was 3.55 (SD = 1.20) on the 0-6 scale. The two scores were moderately correlated ($r = .369$, $p < .001$). This result is useful because it shows both connection and distinction. Students who performed well when interpreting or producing morphology representations also tended to perform well on morphology-based spatial transformations, but the correlation was not large enough to suggest that the two instruments were measuring the same ability. In practical terms, being able to recognize and communicate diagnostic features does not automatically mean that a student can mentally transform a structure from a different orientation, and the reverse is also possible.

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The bivariate correlations showed a clear contrast between the cognitive-load dimensions. Extraneous load was negatively related to representational ability ($r = -.364$, $p < .001$) and spatial ability ($r = -.210$, $p < .001$). Germane load showed the opposite pattern, with positive correlations for representational ability ($r = .273$, $p < .001$) and spatial ability ($r = .216$, $p < .001$). Metacognition was also positively related to both outcomes ($r = .235$, $p < .001$; $r = .189$, $p = .002$). Intrinsic load behaved differently: its correlation with representational ability was small and nonsignificant ($r = -.107$, $p = .074$), and its correlation with spatial ability was close to zero ($r = -.041$, $p = .495$). At the bivariate level, therefore, intrinsic load was not significantly associated with either outcome, whereas extraneous and germane load showed significant associations. Within this sample and with the measures used, extraneous and germane load demonstrated more consistent statistical relationships with visual-representational performance than intrinsic load. This pattern should not be interpreted as evidence that inherent task complexity is unimportant.

The moderate relationship between the two outcomes is also the reason we did not analyze them only as two unrelated dependent variables. Morphology students may face one difficulty when they have to express what they see and another when they have to mentally manipulate the same structure. For example, drawing the diagnostic features of a compound leaf requires coordination between observation and external representation, whereas recognizing the same leaf after a change in orientation places a stronger demand on internal spatial transformation. A multivariate model is useful here because it can identify predictors that operate across both forms of performance, while the follow-up regressions still show whether the strength of those relationships differs for each outcome.

Table 2.
Descriptive statistics and bivariate correlations with the visual-representational outcomes

Variable	M	SD	Range	Representational r (p)	Spatial r (p)
Representational ability	15.66	3.88	5.02-24.00	—	.369 (<.001)
Spatial ability	3.55	1.20	0-6	.369 (<.001)	—
Metacognition	3.38	0.52	1.88-4.84	.235 (<.001)	.189 (.002)
Intrinsic load	6.25	1.45	2.43-10.00	-.107 (.074)	-.041 (.495)
Extraneous load	5.61	1.55	1.20-9.56	-.364 (<.001)	-.210 (<.001)
Germane load	6.90	1.29	3.45-10.00	.273 (<.001)	.216 (<.001)

3.2. Multivariate cognitive-load architecture

When the four predictors were entered together, the multivariate model for the two outcomes was significant, Pillai's $V = .209$, $F(8, 550) = 8.03$, $p < .001$. The predictor-level tests showed that this overall result was driven mainly by two dimensions of cognitive load. Extraneous load had the

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largest multivariate association, Pillai's V = .098, F(2, 274) = 14.81, p < .001, followed by germane load, V = .043, F(2, 274) = 6.07, p = .003. Metacognition was not significant once the load dimensions were considered simultaneously, V = .017, F(2, 274) = 2.30, p = .102. Intrinsic load was also nonsignificant, V = .002, F(2, 274) = 0.26, p = .775.

The contrast between intrinsic and extraneous load should be interpreted cautiously. The biological complexity of plant morphology remains real: students must coordinate several diagnostic characters and relationships before they can identify structures accurately. In the present models, intrinsic load did not make an independent contribution, whereas extraneous load did. This pattern is compatible with studies showing that poorly organized or difficult-to-use biology resources can divert attention from relevant processing (Kastaun et al., 2021; Koć-Januchta et al., 2022), as well as Indonesian studies identifying extraneous load as a challenge in cell biology and plant-tissue learning (Ermayanti et al., 2023; Juanengsih et al., 2021). However, those studies involve different learners, content, and learning environments, so agreement in direction should not be taken as evidence of an identical mechanism. The current cross-sectional self-report data also cannot distinguish whether unnecessary processing demands contribute to lower performance, whether students who struggle subsequently perceive greater extraneous load, or whether both reflect other unmeasured learning conditions. Accordingly, the practical implication is a testable design hypothesis: preserve necessary biological complexity while minimizing avoidable presentation demands, rather than treating the nonsignificant intrinsic-load coefficient as evidence that inherent complexity matters less.

Table 3.
Multivariate tests for representational and spatial abilities as joint outcomes

Effect	Pillai's V	F	df	p
All predictors jointly	.209	8.03	8, 550	< .001
Metacognition	.017	2.30	2, 274	.102
Intrinsic load	.002	0.26	2, 274	.775
Extraneous load	.098	14.81	2, 274	< .001
Germane load	.043	6.07	2, 274	.003

3.3. Outcome-specific models

The outcome-specific model for representational ability was significant, F(4, 275) = 15.64, p < .001, and explained 18.5% of the variance (adjusted R-squared = .173). Extraneous load had the largest standardized coefficient (B = -0.787, beta = -.314, p < .001). After the other predictors were held constant, students reporting greater extraneous load tended to obtain lower scores on the morphology representation tasks. Germane load showed a smaller association in the opposite direction (B = 0.542, beta = .180, p = .002). Metacognition was positive but did not reach the .05

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significance level (beta = .105, p = .075), while intrinsic load made little contribution (beta = .025, p = .672).

The spatial-ability model was also significant, F(4, 275) = 6.51, p < .001, although the explained variance was lower (R-squared = .087; adjusted R-squared = .073). The direction of the two significant load coefficients was the same as in the representational model. Extraneous load was negatively associated with spatial ability (B = -0.132, beta = -.171, p = .007), whereas germane load was positively associated with it (B = 0.141, beta = .152, p = .015). Metacognition again had a positive but nonsignificant coefficient (beta = .103, p = .099), and intrinsic load remained nonsignificant (beta = .041, p = .501).

The directions of the two significant load coefficients were consistent across outcomes, but the explanatory strength differed substantially: the representational model accounted for 18.5% of the variance, whereas the spatial model accounted for 8.7%. The present data cannot identify a single reason for this difference. One possibility is construct proximity: the operational load items describe learning and material conditions that may align more closely with reading, coordinating, and constructing explicit morphology representations. A second possibility is measurement. Representational ability was assessed with eight tasks scored over a 0-24 range, whereas spatial ability used six dichotomously scored items over a 0-6 range; the lower score granularity of the spatial measure may limit detectable variance and attenuate associations. A third possibility is omitted-variable influence, because spatial performance may also depend on visuospatial resources or prior spatial experience that were not measured here. Anatomy research indicates that spatial performance can reflect both individual visuospatial resources and the representational environment (Aspanani et al., 2023; Ho et al., 2022; Koh et al., 2023; Labranche et al., 2022; Sarilita et al., 2022; Wang & McWatt, 2023). These explanations are competing hypotheses rather than mechanisms tested in this study. Future work should use richer item-level spatial measures, independent visuospatial assessments, and site-level information to determine why the spatial model is weaker.

Table 4.

Multiple regression predicting representational ability (n = 280)

Predictor	B	SE	beta	p
Metacognition	0.778	0.436	.105	.075
Intrinsic load	0.066	0.155	.025	.672
Extraneous load	-0.787	0.148	-.314	< .001
Germane load	0.542	0.176	.180	.002

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Table 5.
Multiple regression predicting spatial ability (n = 280)

Predictor	B	SE	beta	p
Metacognition	0.236	0.143	.103	.099
Intrinsic load	0.034	0.051	.041	.501
Extraneous load	-0.132	0.049	-.171	.007
Germane load	0.141	0.058	.152	.015

We also repeated the follow-up models after adding gender and semester indicators. The main pattern did not change. In the representational model, extraneous load remained negative (beta = -.311, $p < .001$) and germane load remained positive (beta = .185, $p = .002$); neither gender nor semester was significant. The same was true for spatial ability: extraneous load remained negative (beta = -.170, $p = .007$) and germane load remained positive (beta = .158, $p = .012$), while the additional controls were nonsignificant. These checks do not make the design causal, but they do show that the central relationships were not simply produced by the unequal gender composition of the sample or by the proportion of students from different semesters.

The semester result deserves some caution in a cross-regional study. A sixth-semester student at one participating program may not have encountered exactly the same sequence of morphology-related learning experiences as a sixth-semester student at another site. For that reason, semester should not be read as a precise indicator of identical curricular exposure. Even so, the absence of a semester effect after the focal predictors were entered suggests that the extraneous- and germane-load pattern is not merely a reflection of academic seniority. The nonsignificant gender control leads to a similar conclusion: the main result is better understood as a learning-process pattern in this sample than as a consequence of its demographic composition. Future studies that retain institutional identifiers could test whether particular instructional practices or curriculum designs strengthen or weaken these relationships.

The positive coefficient for germane load describes the other side of the observed pattern, but it should be read within the operational definition of the parent instrument. Here, germane load represents self-reported effort directed toward organizing and integrating information. Activities such as comparing several representations or explaining why a diagram matches a specimen can plausibly involve this kind of effort (Gardner et al., 2024; Knain et al., 2021; Sripathi & Hoskinson, 2024; Tang et al., 2022). Related evidence from Newman et al. (2023) shows that biological visual expertise is associated with attention to conceptually diagnostic rather than merely superficial features. Nevertheless, a positive self-report coefficient does not establish a distinct causal mechanism. It may partly reflect productive engagement, confidence, prior expertise, or other unmeasured characteristics. The present result therefore supports an association between the

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operational germane-load score and both outcomes, not a claim that increasing a latent germane-load construct will necessarily improve performance.

Metacognition produced a less straightforward result. Its bivariate correlations with both outcomes were significant, but it did not make a statistically significant unique contribution after the three load dimensions were entered simultaneously. This contrasts with studies linking metacognitive monitoring, reflection, and study strategies to biology performance (Behrendt et al., 2024; Bernacki et al., 2023; Ewell et al., 2023; Knight et al., 2022), and with intervention studies showing that metacognitive prompts can strengthen awareness and strategy use (Angell et al., 2024; Elsner & Großschedl, 2024; Ruth & Dzara, 2025). Several explanations are possible. Variance shared with the cognitive-load self-reports may reduce the unique metacognitive coefficient; the 12-item self-report measure may not capture task-specific monitoring during a particular morphology item; and the cross-sectional design cannot establish temporal ordering. The result should therefore not be interpreted as showing that metacognition is unimportant. It indicates only that, for these outcomes and this set of simultaneous predictors, the operational load measures were more proximal statistical correlates than the metacognition score.

The nonsignificant intrinsic-load coefficient should not be converted into an instructional claim that morphology ought to be simplified. Students still need to work with authentic structural variation, distinguish multiple organ types, and use precise botanical terminology. A more conservative implication is to retain this necessary complexity while testing ways to reduce demands that do not contribute to understanding. For example, Koć-Januchta et al. (2022) showed that usability and organization of biology learning resources are related to cognitive processing, while Kastaun et al. (2021) demonstrated the importance of examining how multimedia-supported inquiry environments distribute cognitive demand. Learning materials can therefore be experimentally tested using consistent terminology from text to diagram, labels positioned close to the structures they identify, fewer decorative elements that compete for attention, and comparison sequences that progressively coordinate diagnostic relations. Because the present study is correlational, these are design principles for experimental testing rather than effects demonstrated by the current data.

These results can be translated into fairly concrete morphology-learning activities. Students can be asked to place two similar leaf or inflorescence diagrams side by side and annotate the features that actually distinguish them. They can observe a real specimen from several angles, make a scientific sketch, and then explain which features were preserved or changed in the two-dimensional representation. A mental-rotation task can be followed by a request to justify the answer rather than simply choose an option. Short prompts such as 'Which feature made you decide this?' or 'What evidence would make you change your identification?' can introduce metacognitive checking without turning the activity into a separate lesson on metacognition. In this way, representational practice, spatial reasoning, management of cognitive load, and monitoring of understanding can occur within the same morphology task rather than as four disconnected instructional components.

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The findings should be interpreted within several limitations. First, the data are cross-sectional and correlational, so the coefficients describe associations and cannot establish that changing cognitive load will cause changes in visual competence. Second, this is a secondary analysis of a dataset that was also used for a parent misconception-focused analysis. The present outcomes and multivariate model are different, but the participant dataset and several explanatory measures overlap; this data provenance should be considered when judging the independence of the evidence. Third, participants came from several study regions, but the sample was not a national probability sample. Institution-level identifiers, recruitment counts, response-rate records, and stratum-specific sampling information were not retained in the de-identified analytic file, preventing site-level modeling, cluster-robust standard errors, and a fuller assessment of selection processes. Fourth, exact Aiken's V results, validator characteristics, pilot data, and scale-specific alpha/omega coefficients were not available in the secondary-analysis file and could not be recomputed. This is an important measurement limitation, especially for cognitive-load subscales containing only three or four items. Fifth, cognitive load and metacognition were measured through self-report and may not capture fluctuations during individual morphology tasks. The outcome measures also differ in scoring granularity: representational ability used eight tasks over a 0-24 range, whereas spatial ability used six dichotomously scored items over a 0-6 range, which may partly contribute to the weaker spatial model. Finally, aggregate scores can conceal concept-level differences; phyllotaxy, inflorescence, modified organs, and ovary position may impose different cognitive demands. Future research should combine richer psychometric documentation, site-level sampling information, concept-level analyses, process data or eye tracking, and longitudinal or experimental designs.

4. Conclusion

The results show a consistent pattern of association between the measured cognitive-load conditions and visual-representational competence in plant morphology. Among the 280 pre-service biology teachers, higher extraneous-load scores were associated with lower representational and spatial performance, while the operational germane-load score showed smaller positive associations with both outcomes. These relationships remained after gender and semester were added to the models. Intrinsic load did not show a statistically significant independent contribution, and metacognition, although positively related to both outcomes at the bivariate level, was not significant after the load dimensions were considered together. These findings do not imply that inherent task complexity or metacognition is unimportant; rather, within this sample and measurement framework, extraneous and germane load showed the most consistent unique associations with both outcomes. For morphology teaching, the results justify testing instructional designs that preserve necessary biological complexity while reducing avoidable processing demands and supporting meaningful comparison, construction, rotation, annotation, and justification of representations. Experimental research with stronger measurement documentation and site-level sampling information is needed before causal instructional claims can be made.

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