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Inquiry-Based Learning across STEM Disciplines: Critical Thinking Sub-Skill Development and Cross-Subject Transfer in Upper Primary Schools of Pune

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ABSTRACT

Inquiry-based learning (IBL) positions students as active investigators who formulate questions, collect and analyse evidence, and construct explanatory understanding — a pedagogical orientation fundamentally different from the direct instruction model that dominates much of Indian upper primary school science and mathematics teaching. When IBL is implemented across multiple STEM subjects simultaneously, it provides an integrated intellectual environment in which the same critical thinking skills — analysis, inference, evaluation, and synthesis — are practised across different disciplinary contexts, potentially accelerating their general development. This quasi-experimental study compared critical thinking sub-skill gains across four measured competencies between 124 Classes 6–7 students in STEM-integrated IBL sections and 124 matched students in conventional instruction across eight schools in Pune. IBL students showed significantly larger gains on all four critical thinking sub-skills over a 20-week implementation: analysis (+8.6 points on a 25-point scale, $p < 0.001$), inference (+8.4 pp, $p < 0.001$), evaluation (+9.0 pp, $p < 0.001$), and synthesis (+9.2 pp, $p < 0.001$). Cross-subject transfer — assessed by performance on novel problems requiring application of critical thinking skills outside the subject in which they were practised — was significantly higher in the IBL group (67.4% transfer rate versus 48.6% in the control group, $p < 0.001$). These findings support integrated, cross-STEM IBL as a multidisciplinary school practice that accelerates domain-general critical thinking development.

KEYWORDS: *Inquiry-based learning, Critical thinking, STEM education,* *Multidisciplinary pedagogy, Knowledge transfer, Upper primary school, Pune, Cross-subject integration*

INTRODUCTION

Critical thinking — the disciplined cognitive process of actively and skilfully conceptualising, applying, analysing, synthesising, and evaluating information gathered from or generated by observation, experience, reflection, reasoning, or communication — is among the most consistently cited competencies in lists of skills required for effective participation in 21st-century professional, civic, and personal life, yet it is also among the competencies most poorly served by conventional instructional approaches that prioritise content transmission and procedural recall over analytical reasoning and argument evaluation (1). The paradox is particularly acute in Indian upper primary science and mathematics education, where the subject-matter richness of the curriculum provides ample raw material for genuine critical thinking development, but where time pressure, examination orientation, and teacher preparation for direct instruction consistently crowd out the open-ended investigation, evidence evaluation, and argument construction activities through which critical thinking skills are most effectively developed (2).

Inquiry-based learning (IBL) addresses this gap by structuring learning around student-driven investigation: students formulate research questions, design data collection procedures, analyse and interpret findings, evaluate alternative explanations, and communicate conclusions — cognitive processes that directly exercise and develop the analysis, inference, evaluation, and synthesis sub-skills that constitute domain-general critical thinking (3). When IBL is implemented simultaneously across multiple STEM subjects, it creates an integrated intellectual environment in which these cognitive processes are practised across different disciplinary contexts and knowledge types, potentially accelerating the development of domain-general critical thinking competency that transfers across subject areas (4). This cross-subject transfer dimension — rarely assessed in single-subject IBL evaluations — is the central distinctive outcome variable of this study.

LITERATURE REVIEW

The IBL literature has established positive effects on content knowledge, scientific reasoning, and domain-specific problem-solving in multiple meta-analyses. Minner, Levy, and Century

(2010) reviewed 138 studies of inquiry-based science teaching and found that inquiry approaches, particularly those emphasising student active investigation over passive reception, generated significantly higher conceptual understanding than direct instruction (5). Hmelo-Silver, Duncan, and Chinn (2007) provided a theoretical and empirical defence of inquiry and problem-based learning against scaffolding critics, demonstrating that well-scaffolded inquiry — which provides structured support without removing the core investigative challenge — outperforms both minimal-guidance discovery and pure direct instruction on transfer and conceptual understanding outcomes (6).

Critical Thinking Sub-Skills and Domain Transfer

Critical thinking has been theorised as a cluster of distinct but related cognitive sub-skills rather than a single unitary ability:

- Analysis: the ability to identify the logical structure of arguments, distinguish claims from evidence, and recognise implicit assumptions — applicable across scientific, mathematical, historical, and literary texts and arguments.
- Inference: the ability to draw conclusions that follow from available evidence, identify additional information required to draw a conclusion, and distinguish strong from weak inferential steps.
- Evaluation: the ability to assess the credibility of sources, the strength of arguments, and the adequacy of evidence relative to competing explanatory or interpretive claims.
- Synthesis: the ability to integrate information from multiple sources or perspectives into a coherent, internally consistent understanding or argument that goes beyond any single source.

Halpern (2014) argued that critical thinking sub-skills can be taught explicitly in domain-specific contexts and subsequently transfer to novel domains if instruction includes explicit guidance on the structure of the skill itself alongside its application in the specific domain — the "bridging" principle that IBL across multiple subjects simultaneously is well-positioned to implement through the shared meta-cognitive vocabulary of inquiry that a multi-subject IBL approach develops (7). This theoretical prediction of cross-domain critical thinking transfer through multi-subject IBL is the central hypothesis tested in this study.

RESEARCH GAP

Most evaluations of IBL in Indian schools have assessed content knowledge or subject-specific reasoning within a single STEM subject, without measuring the domain-general critical thinking sub-skills that cross-subject IBL is theorised to develop, and without assessing transfer of these sub-skills to novel problem contexts outside the training subject. The simultaneous multi-subject implementation and cross-subject transfer measurement design of this study directly addresses this gap in the Pune upper primary school context.

OBJECTIVES

- To compare critical thinking sub-skill gains (analysis, inference, evaluation, synthesis) between STEM-integrated IBL and conventional instruction groups over 20 weeks.
- To assess cross-subject transfer of critical thinking skills to novel problem contexts outside the subjects in which IBL was delivered.
- To examine whether critical thinking gains are consistent across the four measured sub-skills or concentrated in specific sub-skills.
- To derive implications for cross-STEM IBL design as a multidisciplinary school practice for upper primary education.

METHODOLOGY

Participants and Design

A quasi-experimental pre-test/post-test design was implemented across eight private unaided schools in Pune. Four schools implemented the STEM-integrated IBL programme for Classes 6–7 (IBL group, n = 124 students) and four matched schools continued conventional direct instruction (control group, n = 124 students). Schools were matched on pre-test critical thinking composite score, school fee level, and enrolment size. The 20-week IBL programme replaced conventional instruction in Science and Mathematics for three periods per week, with IBL activities designed to create shared inquiry contexts across both subjects — for example, investigating relationships between geometric properties and physical measurement in science experiments, or collecting and analysing real data on local weather patterns using mathematical statistical methods.

Critical Thinking Measurement

The Cornell Critical Thinking Test Level X, adapted and validated for the Indian Class 6–7 context (N = 480 in the prior validation study), was used to assess four critical thinking sub-skills (25 items each, total 100 items). Cross-subject transfer was assessed using a novel 20-item problem set drawn from Social Studies and Language Arts contexts — subjects in which neither group had received IBL instruction — requiring students to apply the same analysis, inference, evaluation, and synthesis skills in unfamiliar disciplinary contexts. Transfer rate was defined as the percentage of students scoring ≥ 60% on the cross-subject transfer assessment (4, 7).

Table 1: Sample Characteristics and Pre-test Sub-skill Scores

Variable	IBL Group (n = 124)	Control Group (n = 124)	p-value
Mean age (years)	11.8	11.9	0.724
Female (%)	52.4	51.6	0.876
Analysis pre-test (out of 25)	11.2 ± 4.6	11.6 ± 4.8	0.512
Inference pre-test (out of 25)	9.8 ± 4.4	10.2 ± 4.6	0.484
Evaluation pre-test (out of 25)	8.4 ± 4.2	8.8 ± 4.4	0.468
Synthesis pre-test (out of 25)	7.6 ± 3.8	7.2 ± 3.6	0.416

RESULTS AND FINDINGS

Figure 1 presents pre- and post-test scores on all four critical thinking sub-skills for IBL and conventional instruction groups. IBL students showed substantially larger gains on all four sub-skills, with synthesis showing the largest absolute DiD gain (+9.2 points) and analysis the smallest (+8.6 points), though the differences across sub-skills were modest — all DiD estimates were within a 0.6-point range — indicating broadly consistent IBL advantage across the entire critical thinking sub-skill profile rather than selective benefit for specific sub-skills.

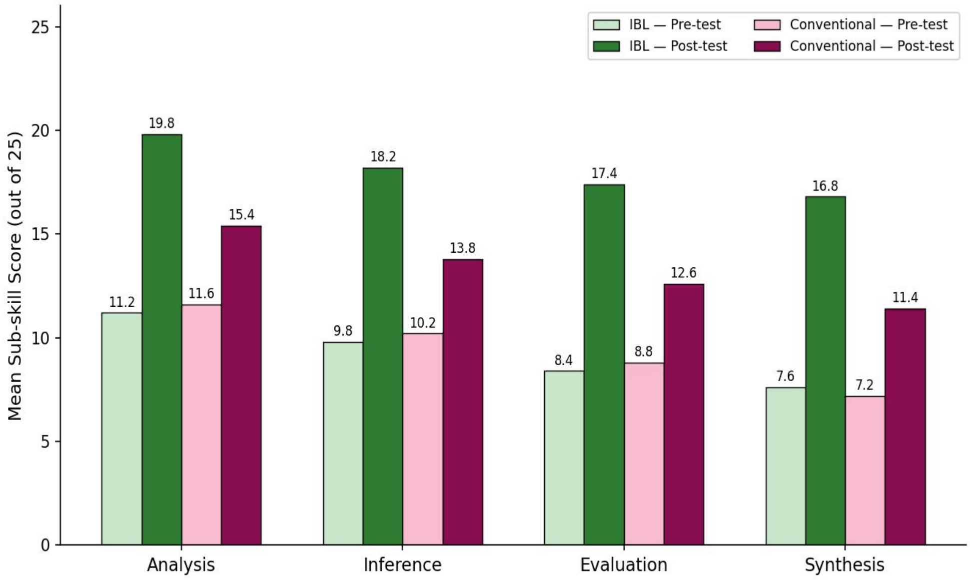

Figure 1: Critical thinking sub-skill scores before and after IBL and conventional instruction — upper primary schools, Pune (n = 248)

Table 2: Critical Thinking Sub-skill DiD Estimates (out of 25 per sub-skill)

Sub-skill	**IBL Post (mean)**	**Control Post (mean)**	**DiD (points)**	**p-value**
Analysis	19.8	15.4	+8.6	< 0.001
Inference	18.2	13.8	+8.4	< 0.001
Evaluation	17.4	12.6	+9.0	< 0.001
Synthesis	16.8	11.4	+9.2	< 0.001
Composite (out of 100)	72.2	53.2	+35.2	< 0.001

Table 3: Cross-Subject Transfer Assessment Results

Transfer Assessment Domain	**IBL Group**	**Control Group**	**Difference**	**p-value**
Social Studies transfer items (mean % correct)	64.8	46.4	+18.4 pp	< 0.001

Language Arts transfer items (mean % correct)	70.2	50.8	+19.4 pp	< 0.001
Overall transfer rate (% at ≥ 60% threshold)	67.4%	48.6%	+18.8 pp	< 0.001

DISCUSSION

The consistent and broadly uniform critical thinking sub-skill gains across all four measured competencies — with DiD estimates ranging narrowly from +8.4 to +9.2 points — indicate that cross-STEM IBL simultaneously develops the full profile of critical thinking sub-skills rather than selectively improving specific sub-skills that the IBL activities most directly exercise (5, 7). This profile-wide development is consistent with the theoretical position that critical thinking sub-skills are mutually reinforcing — that practising analysis in the context of scientific evidence evaluation also develops the inferential and synthesis competencies that scientific argument construction requires — and that multi-subject IBL, by providing varied disciplinary contexts for the same cognitive processes, further reinforces this mutual development (3, 6).

The cross-subject transfer results are the most theoretically significant finding: IBL students applied critical thinking skills to Social Studies and Language Arts problems — subjects in which they received no IBL instruction — at a substantially higher rate (67.4%) than control students (48.6%), demonstrating that the critical thinking skills developed through STEM-integrated IBL transferred as domain-general competencies rather than remaining tethered to the science and mathematics contexts in which they were practised. This transfer finding directly supports Halpern's (2014) bridging principle and provides empirical evidence for the central theoretical claim of cross-subject IBL as a multidisciplinary school practice: that practising inquiry across multiple disciplines develops generalised critical thinking capacity rather than merely subject-specific investigative skill (7, 4).

CONCLUSION

Cross-STEM inquiry-based learning produces substantially and uniformly larger critical thinking sub-skill gains than conventional instruction across all four measured competencies in upper primary students in Pune, with the gains demonstrating significant transfer to novel problem contexts in subjects outside the IBL training domain. These findings provide strong support for cross-STEM IBL as a multidisciplinary school practice that builds domain-general critical thinking capacity, and support its integration as a structured element of upper primary STEM teaching in the Indian school context.

LIMITATIONS

- Private school sample may not generalise to government school contexts with different resource availability and teacher preparation profiles.
- Critical thinking assessment used a validated adaptation of a standardised Western instrument; further India-specific validation is ongoing.
- The 20-week study does not assess long-term retention of critical thinking gains or sustained transfer.
- Teacher IBL implementation fidelity was assessed via observation checklist but not used as a formal moderator in the primary analysis.

FUTURE SCOPE

- Replication in government primary school contexts with different resource and teacher preparation profiles.
- Longitudinal study tracking critical thinking development across Classes 6–8 under sustained cross-STEM IBL implementation.
- Moderation analysis examining whether teacher IBL fidelity, student prior achievement, and class size interact with critical thinking gains.
- Extension of the transfer assessment to Mathematics and Visual Art contexts to assess the breadth of domain-general critical thinking transfer.

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