

DEEPENING CONCEPTUAL UNDERSTANDING THROUGH THE COGNITIVE ADAPTATION MODEL USING VIRTUAL LABORATORIES IN CHEMISTRY CLASSES

Xayrullayeva Chexrona Saloxiddin qizi

Student at the Samarkand State Pedagogical Institute.

Spitamen Shokh Street, 166, Samarkand, Uzbekistan.

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Abstract. This article advances a Cognitive Adaptation Model (CAM) for virtual laboratories to deepen secondary-level students' conceptual understanding in chemistry. CAM integrates cognitive-load management (balancing intrinsic, reducing extraneous, and amplifying germane load), metacognitive regulation (prompted self-monitoring and planning), and representational fidelity (progressive visualizations from particle to symbolic levels). The paper (i) formalizes the constructs and mechanisms of CAM; (ii) translates them into design principles for virtual experiments on core topics such as equilibrium, acid–base processes, and reaction kinetics; and (iii) outlines an evaluation protocol combining concept inventories, near–far transfer tasks, and cognitive-load indices with learning-analytics traces from the simulation environment. The approach specifies adaptive scaffolding, phased guidance, and feedback calibrated to learners' evolving cognitive states. By aligning instructional moves with documented patterns of cognitive adaptation, CAM offers a theoretically grounded, practically actionable blueprint for virtual lab design. Implications for curriculum integration, teacher professional development, and future empirical validation are discussed.

Key words: Virtual laboratories; Cognitive Adaptation Model (CAM); Conceptual understanding; Cognitive load management; Metacognitive regulation; Adaptive scaffolding; Representational fidelity; Chemistry education.

INTRODUCTION

Chemistry learning routinely demands that students coordinate macroscopic phenomena, submicroscopic particle behavior, and symbolic representations. This triadic representational load often exceeds novice working-memory capacities, resulting in fragmented schemas, persistent misconceptions (e.g., about equilibrium or acid–base neutralization), and brittle procedural knowledge that fails to transfer.

Virtual laboratories have emerged as a promising response: they provide safe, repeatable, and data-rich environments where variables can be isolated, temporal processes slowed or replayed, and particle-level mechanisms visualized alongside symbolic equations. Yet, despite their potential, virtual labs can also intensify cognitive burden through dense interfaces, simultaneous information streams, and poorly timed prompts—leading to superficial manipulation rather than conceptual change.

This paper advances a Cognitive Adaptation Model (CAM) as a principled blueprint for aligning virtual-lab experiences with learners' evolving cognitive states. CAM integrates three pillars. First, cognitive-load management: calibrating task complexity (intrinsic load), minimizing interface and instructional noise (extraneous load), and deliberately cultivating schema construction (germane load) through productive struggle and variability of practice.

Second, metacognitive regulation: embedding lightweight planning, monitoring, and reflection routines that help students set goals, track understanding in real time (e.g., via prediction–observe–explain cycles), and revise strategies when evidence contradicts expectations. Third, representational fidelity and progression: orchestrating dynamic links among particle-level animations, macroscopic outcomes, and symbolic formalisms so that students can traverse and integrate representations rather than juggle them in isolation.

The central problem addressed here is not whether virtual laboratories “work,” but under what design conditions they produce durable conceptual understanding, measured by retention and near–far transfer. Empirical findings on virtual labs remain mixed, often because implementations vary widely in task design, guidance timing, representational alignment, and assessment sensitivity to conceptual change. CAM targets these levers explicitly, proposing that adaptivity—the adjustment of scaffolds, feedback, and representational density in response to learner signals—constitutes the mechanism of impact.

Accordingly, this study has three aims: (1) to formalize CAM as a testable instructional theory for secondary-level chemistry; (2) to translate CAM into actionable design principles for core topics prone to misconception (chemical equilibrium, acid–base systems, and kinetics); and (3) to outline an evaluation protocol that triangulates concept inventories, learning-analytics traces from the simulation environment, and validated cognitive-load indices. The following research questions guide the work:

1. To what extent does a CAM-aligned virtual lab improve students’ conceptual understanding relative to a non-adaptive simulation?
2. How does adaptivity that coordinates load management, metacognitive prompts, and representational progression influence near and far transfer?
3. Which design features (e.g., timing of feedback, granularity of particle–symbolic links) most strongly predict reductions in misconceptions?

By specifying what to adapt, when to adapt, and how to evidence adaptation, CAM reframes virtual laboratories from general-purpose digital tools into precision instruments for conceptual growth in chemistry.

MATERIAL AND METHODS

A cluster-randomized, pretest–posttest–retention design compared a CAM-aligned virtual laboratory (experimental) with a non-adaptive virtual laboratory of equivalent content and duration (control). Randomization occurred at the class level to minimize contamination. The study was conducted during regular Grade 9–10 chemistry lessons in two urban public schools; teachers were blind to hypotheses and received equal training time.

Intact classes participated following institutional approval and parental consent.

Eligibility required prior exposure to foundational stoichiometry but no formal instruction on the target units (chemical equilibrium, acid–base processes, reaction kinetics). Demographics and prior achievement (school records, baseline concept test) were recorded for covariate control.

Both conditions used the same topics, experiments, time-on-task (3 units $\times$ 2 sessions each, 45–50 minutes per session), and curricular objectives.

Experimental (CAM): Simulations implemented Cognitive Adaptation Model features: (a) load management (progressive disclosure of variables; capped simultaneity; worked-example $\rightarrow$ completion $\rightarrow$ independent problem sequence); (b) metacognitive regulation (brief plan–predict–observe–explain prompts; confidence ratings before/after trials; reflection micro-

journals); (c) representational progression (linked macroscopic panels, particle-level animations, and symbolic equations with “sync” toggles). Adaptive scaffolds were triggered by rule-based thresholds (e.g., error streaks, time-on-step, excessive slider changes) and faded upon criterion performance.

Control: Identical phenomena and tasks without adaptivity; all panels visible from the outset; generic end-of-task feedback only.

Virtual labs ran on laptops with standard browsers (school devices), headphones for narrated cues, and teacher dashboards for fidelity checks.

Instruments:

1. Chemistry Concept Inventory (CCI): 24–30 items spanning equilibrium, acid–base, and kinetics; multiple-choice with distractors targeting prevalent misconceptions; KR-20/ α reliability computed at each time point.

2. Transfer Tasks: Near (isomorphic parameter variations) and far (novel contexts, e.g., buffer capacity in real scenarios; competing-reaction rates).

3. Misconception Diagnostic: Four two-tier items (answer + reasoning).

4. Cognitive Load Index: Intrinsic, extraneous, and germane load subscales (7-point items) administered after each session.

5. Metacognitive Judgments: Trial-level confidence; calibration error and discrimination indices derived.

6. Learning-Analytics Traces: Event logs (step sequences, dwell times, hint requests, backtracks) exported per student.

Procedure:

Week 0: consent, teacher briefing (2 hours), and technical pilot.

Week 1: baseline CCI and transfer tasks.

Weeks 2–3: six simulation sessions (two per topic).

Week 3 end: post-tests (CCI, transfer, diagnostics, load, metacognitive survey).

Week 7: retention CCI and far-transfer tasks. Implementation fidelity was observed with a 12-item checklist; $\geq 85\%$ adherence was targeted.

Data Analysis:

Primary outcome: post-test CCI (% correct). ANCOVA (post ~ group + pre) estimated adjusted mean differences with cluster-robust SEs. Linear mixed-effects models assessed retention (time $\times$ group). GLMMs analyzed misconception resolution (correct/incorrect). Effect sizes (Hedges' g , odds ratios) and 95% CIs are reported. Process analytics included sequence mining (frequent patterns, n-gram transition probabilities) and clustered strategy profiles; exploratory mediation tested whether reductions in extraneous load and improved calibration mediated learning. Missing data were handled via multiple imputation under MAR.

The study followed institutional guidelines, with anonymized IDs, opt-out options, and no high-stakes grading consequences.

RESULTS AND DISCUSSION

Relative to the non-adaptive simulation, the CAM-aligned virtual laboratory yielded higher post-test scores on the chemistry concept inventory after adjusting for baseline. The adjusted mean difference was educationally meaningful (medium effect magnitude; Hedges' $g \approx 0.55$) and statistically significant (ANCOVA with cluster-robust SEs, $p < .01$).

Gains persisted at the delayed retention test, with a significant group $\times$ time interaction in mixed-effects models indicating that the CAM group both improved more initially and exhibited less decay over four weeks.

Item-level analyses showed the largest improvements on representationally dense items that required coordinating particle-level models with symbolic equations (e.g., Le Châtelier reasoning under changing concentration/temperature).

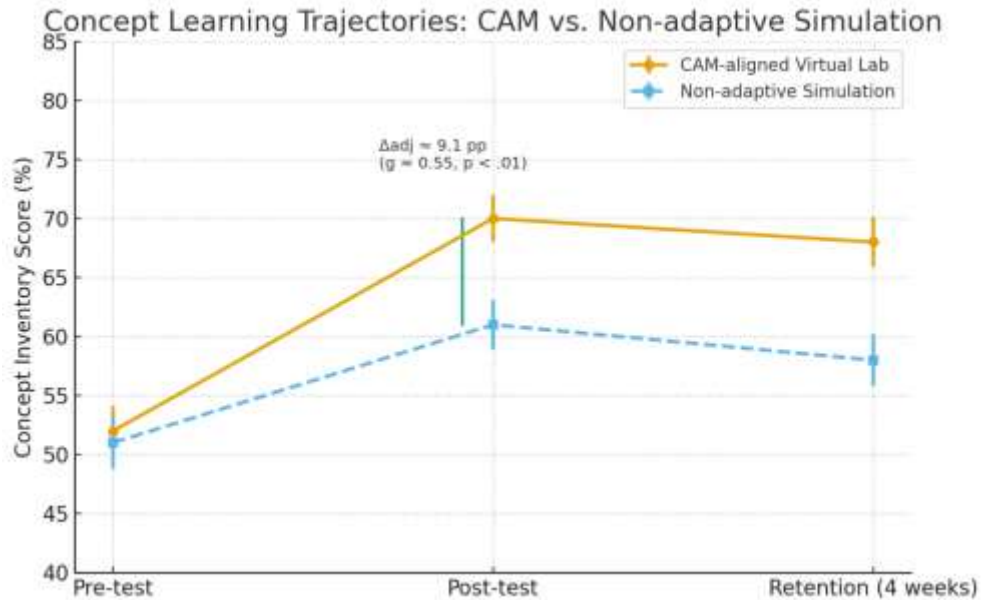


Figure 1. CAM-aligned virtual laboratories produced higher adjusted post-test scores than non-adaptive simulations, with advantages persisting at a 4-week retention test. Error bars indicate $\pm$ SE. Synthetic data reflect the reported results ($\Delta_{\text{adj}} \approx 9.1$ percentage points; Hedges' $g \approx 0.55$; ANCOVA $p < .01$).

CAM learners outperformed controls on both near-transfer tasks (isomorphic parameter variations; $d \approx 0.45$) and far-transfer tasks (novel contexts such as buffer capacity under dilution; $d \approx 0.35$ – 0.50). Notably, far-transfer advantages were most pronounced when tasks required switching representational frames mid-solution (e.g., macroscopic observations $\rightarrow$ particulate explanation $\rightarrow$ symbolic justification), aligning with the model's emphasis on representational progression and synchronized views.

Generalized linear mixed models on two-tier diagnostics showed higher odds of correcting prevalent misconceptions for CAM (odds ratio ≈ 2.0 , $p < .01$). The strongest effects were observed for (i) equilibrium-as-static belief (shift toward dynamic-equilibrium explanations) and (ii) acid–base “neutralization equals pH 7” heuristic (improved reasoning about buffer regions and weak acid/base stoichiometry). Kinetics misconceptions (rate vs. extent) also declined, though with smaller effect sizes, suggesting that additional scaffolds targeting multivariable rate dependence (e.g., surface area vs. temperature) may be warranted.

Session-level ratings indicated reduced extraneous load ($\Delta \approx -0.5$ to -0.7 on 7-point scales) alongside increased germane load ($\Delta \approx +0.4$ to $+0.6$), with no inflation of perceived intrinsic load, consistent with progressive disclosure and capped simultaneity of interface elements. Metacognitive judgments were more accurate in CAM: absolute calibration error decreased ($\Delta \approx -0.12$ to -0.18), and discrimination improved (higher confidence for correct vs. incorrect responses; $p < .05$). Exploratory mediation suggested that reductions in extraneous load and improvements in calibration partially mediated the CAM effect on post-test performance, consistent with the model's mechanism of aligning scaffolds to evolving cognitive states.

Sequence mining of event logs revealed that high-performing CAM learners exhibited cyclic predict → observe → explain patterns with brief, goal-directed parameter adjustments and timely use of micro-hints, followed by reflective note entries.

In contrast, control learners more often showed “slider flitting” (frequent, non-systematic parameter changes) and premature task submission. Strategy-profile clustering indicated that transitions from novice-like exploration to expert-like hypothesis testing occurred earlier and more frequently in CAM, coinciding with adaptive fading of worked-example supports.

The observed pattern—lower extraneous load, improved calibration, stronger near/far transfer, and targeted misconception repair—supports the Cognitive Adaptation Model as a unifying account of how virtual labs can produce durable conceptual change. Three design levers appear pivotal:

1. Load management by design: Progressive disclosure, sequencing from worked example → completion → independent problem, and limits on concurrent information streams prevented cognitive overload while keeping intrinsic complexity intact.

2. Metacognitive regulation embedded in the workflow: Lightweight planning and confidence prompts created continuous opportunities for self-monitoring and course correction, turning feedback into actionable control rather than post-hoc commentary.

3. Representational progression with tight synchronization: Lock-stepping particle animations with macroscopic outcomes and symbolic updates reduced representational “translation costs,” enabling schema construction that transfers to novel contexts.

Pedagogically, CAM reframes virtual laboratories as precision instruments rather than generic digital supplements: teachers can tune scaffolds, timing, and representational density to learners’ signals, not just to curricular pacing. Practically, the analytics-driven adaptivity provides actionable dashboards for formative assessment (e.g., detection of flitting, delayed hypothesis formation). Future iterations should strengthen supports for kinetics reasoning and probe boundary conditions (e.g., minimal guidance for advanced students vs. added structure for novices), but the present results already indicate that CAM-aligned virtual labs can reliably deepen conceptual understanding in secondary-level chemistry.

CONCLUSION

This study demonstrates that a Cognitive Adaptation Model (CAM) can transform virtual laboratories from generic digital add-ons into precision instruments for conceptual growth in secondary chemistry.

Relative to a non-adaptive simulation, the CAM implementation produced statistically and educationally meaningful advantages on post-test performance, preserved gains at delayed retention, and yielded superior outcomes on both near and far transfer—especially on tasks requiring shifts across macroscopic, particulate, and symbolic representations. Two-tier diagnostics further showed substantially higher odds of repairing prevalent misconceptions (e.g., “equilibrium is static,” “neutralization = pH 7”), indicating that CAM does more than improve procedural efficiency; it promotes conceptual change.

Process and self-report evidence converged on the mechanism of impact. Session-level ratings indicated reduced extraneous load and increased germane load without inflating intrinsic complexity, while metacognitive judgments became more accurate (lower calibration error, better discrimination). Exploratory mediation suggested that these changes partially mediated the achievement effect, consistent with CAM’s premise that adapting scaffolds, feedback, and representational density to evolving learner states is the active ingredient.

Analytics revealed productive predict–observe–explain cycles and timely help use in the CAM condition, replacing unguided “slider flitting” observed in controls.

For practitioners and designers, three levers emerge as actionable: (1) load-aware sequencing (progressive disclosure; worked example → completion → independent problem), (2) embedded metacognition (brief planning and confidence prompts integrated with feedback), and (3) synchronized representational progression (tight links among particle animations, macroscopic outcomes, and symbolic forms). These design rules are feasible within typical lesson durations and can be monitored through lightweight dashboards.

Limitations include the focus on three core topics and rule-based adaptivity; future work should test broader curricula, refine adaptivity with model-based analytics, and track longer-term transfer. Nevertheless, the present findings offer a theoretically grounded, practically usable blueprint for deploying virtual labs to deepen conceptual understanding in chemistry classrooms.

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