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Effect of Cognitive Load Management on Physics Achievement at the Secondary Level

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Abstract

Cognitive Load Theory (CLT) describes that the human brain has a limited working memory with restricted storage and processing capacity. Thus, cognitive load management plays an important role in the preparation of instructional design. Managing cognitive load while teaching subjects like science or mathematics, where problem-solving and high cognitive activity are involved, can enhance effective learning. The current study investigates the effect of cognitive load management on Physics achievement at the secondary level. A quasi-experimental pre- and post-test control group design was used for the CLT intervention. Sixty-four secondary school students, male and female, from a public school, studying the subject of Physics, were taken as the study group. They were randomly distributed into control and experimental groups (N = 32 each). A concept-based, researcher-made pre- and post-test (MCQs) was administered to both groups before and after the intervention (9 months). The pre- and post-test scores of the experimental and control groups were compared using an independent sample t-test. Within-group differences in scores were determined through a paired sample t-test. The experimental group exhibited a significant increase in scores on the concepts of Physics as compared to the control group. The study has implications for the use of precise and evidence-based strategies for reducing cognitive workload in other subjects to promote effective and long-lasting learning.

Keywords: Cognitive Load Theory, Teaching of Physics, Experimental Study

Introduction

Cognitive Load Theory (CLT) explains that our working memory has limited and restricted storage and processing capacity. An earlier study by Miller (1956), reported that working memory can hold and process only seven to nine concepts or elements at a time. Later research further added that the brain keeps only two to four concepts at a time if the concepts are novel (Cowan, 2021; Sweller, 2023; Zhong, Katkov & Tsodyks, 2024). However, if the brain has some previous schema and it can associate new information with the existing concepts, the retention and processing can be increased. On the other hand, if the information is not encoded by the brain due to any reason, it diminishes within 20 seconds. These findings emphasize the need of well-planned instructional designs, which can reduce the cognitive load of learners by linking new ideas with the previous ones and making the associations stronger. Likewise, large number of unknown concepts may not be presented at a time (Baddeley et al., 2022).

Cognitive Load Theory (CLT) further describes that instructional design should minimize extraneous elements that confuse the brain and, instead, activate relevant concepts stored in the learner's long-term memory to form deeper and stronger connections with new information, thereby enhancing coherence (Sweller, van Merriënboer, & Paas, 2019; de Jong, 2025). This approach may improve learning efficiency (Faudzi et al., 2024).

Cognitive Load Theory (CLT)

In recent years, CLT has emerged as an important concept underlying instructional design, whether for formal classroom settings or web-based instruction. It addresses the type and amount of instructional material, its sequence of presentation, the learning environment, the nature of the task, and the intrinsic and extraneous nature of stimuli provided to learners. It is evident that when cognitive load is increased or exceeds the limits of working memory, learning is hindered and suppressed (van Merriënboer, Paas, & Sweller, 2010). Sweller (2010) identified three types of cognitive load: germane load, intrinsic load, and extraneous load, as discussed below:

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1. ***Intrinsic cognitive load*** emerges when the learner's previous knowledge or expertise interact with the new learning material presented and its complexity increases with the number of elements processed at a time in the working memory of the learner (van Merriënboer & Ayres, 2014).
2. ***Extraneous cognitive load*** is caused by a poor instructional design when unnecessary and irrelevant information is imparted to overload the working memory. It contains several elements at a time to raise the cognitive load of the learner (van Merriënboer & Ayers, 2019; Sweller et al., 2011; Sweller, 2010).
3. ***Germane cognitive load*** is related to mental processes like formation of schema and associational connections. This is the copying phenomena of working memory for managing intrinsic load and helps in long term retention and learning (van Merriënboer & Ayres, 2014; Sweller, 2010).

Cognitive Load Effects

Cognitive Load Theory (CLT) identifies several design effects like Modality effect (Sweller, et al., 1990), Split-Attention Effect (Chandler & Sweller, 1992), Expertise Reversal effect (Kalyuga, Ayres, Chandler & Sweller, 2003) and Redundancy effect (Kalyuga, Chandler & Sweller, 1999) which guide effective instruction. For instance, the *modality effect* suggests that pictorial presentation should accompany spoken text instead of written text because it engages students' visual and auditory channels and reduces extraneous load. Likewise, the *split-attention* (spatial contiguity) effect shows that students learn better when related information (e.g. labels or equations) is embedded in diagrams so they do not have to mentally stitch together separate sources (Hatsidimitris & Allen, 2010). Conversely, the *redundancy effect* warns that simultaneous presentation of identical information, for example, having text and narration say the same thing, can overload novice learners' working memory. Finally, the *expertise-reversal effect* implies tailoring support to learners' experience. Novice physics students benefit most from fully worked examples and guided solutions, whereas advanced students learn better when excess guidance is removed.

Instructional Strategies to Manage Cognitive Load

In recent years several physics-education studies have shown that well-designed instructional supports can reduce students' cognitive load effective learning. For example, Dervić et al. (2019) compared interactive Physlet animations with static diagrams in teaching optics and found that the Physlets 'generally lead to higher germane load and more effective learning than the traditional approach' suggesting that interactive multimedia can offload extraneous burden and promote deeper processing. Similarly, Morphew et al. (2020) used animated worked-example videos following multimedia design principles and reported that all video formats supported learning equally well, and that having students attempt problems before viewing solutions aided understanding of moderately difficult problems. Building on these strategies, Dunleavy et al. (2022) introduced very short post-lecture multimedia summaries (one-minute videos plus text) and demonstrated significant gains in students' concept organization; they explicitly attributed this to better chunking of information and minimizing the extraneous cognitive load imposed by the lecture. More recently, Appiah-Twumasi (2024) applied scaffolded instruction to advanced atomic and nuclear physics: his quasi-experimental study found significant post-test gains and more positive learning dispositions after using scaffolds, and he recommends scaffolding explicitly as a cognitive-load reduction strategy. Finally, Wei et al. (2025) compared prerecorded video versus live instruction for physics problem solving and found that while videos were as effective as live teaching on simple problems, live instruction far outperformed video on complex problems. This suggests that adaptive, face-to-face teaching can better modulate cognitive demands when material is difficult. Together, these studies (Dervić et al., 2019; Morphew et al., 2020; Dunleavy et al., 2022; Appiah-Twumasi, 2024; Wei et al., 2025) illustrate that physics instructors can mitigate cognitive load through interactive animations, segmented multimedia, pre-practice, or scaffolding to enhance student learning.

Vasile et al. (2011) found a direct relationship between mental load and academic self-efficacy in educational environments, although they observed consistent variations in self-efficacy between genders. Following this, Wong et al. (2012) concluded that simulations were more effective than static illustrations when knowledge was presented in short segments; however, their superiority diminished for longer transient materials.

Subsequently, Leahy and Sweller (2015) examined the modality effect and revealed that while auditory-visual demonstrations are effective, they may be less impactful than equivalent lengthy graphical presentations when cognitive load is high. Gorjian and Kermanshahi (2017) further supported the value of instructional modality by showing that demonstration methods significantly outperformed text-based approaches in enhancing student learning.

More recently, research by Chen et al. (2021) and Skulmowski & Xu (2023) has reinforced these earlier findings by exploring how visual and spatial instructional formats influence learning outcomes under varying cognitive load conditions, thus offering contemporary support for designing effective multimedia instruction aligned with Cognitive Load Theory in the subject of Physics.

Statement of the Problem

Despite ongoing educational reforms in Pakistan, secondary school students continue to struggle with conceptual understanding in science subjects, particularly Physics (Mirza, 2025). Due to traditional rote-based teaching methods that overlook the cognitive limitations of learners (Jamil, 2024). In many classrooms, instructional practices fail to consider how students process and retain complex information, resulting in cognitive overload and poor academic performance. Cognitive Load Theory (Sweller, 2010) offers a framework to optimize instructional design by aligning teaching methods with the brain's processing capabilities; however, its application remains largely unexplored in Pakistani schools. This study addresses the gap by investigating how Cognitive Load Theory, based instructional strategies can enhance Physics learning outcomes among secondary school students.

Objectives

1. To find out the cognitive load effects like; Split-Attention Effect, Redundancy effect, Modality effect and Expertise Reversal effect on the concepts of Physics at secondary school students.
2. To identify the effect of Cognitive Load Theory on the academic performance of the secondary school students in the subject of physics based on gender difference.

Hypotheses

H_o: There is no significant effect of cognitive load management consisting Split-Attention Effect, Redundancy effect, Modality effect and Expertise Reversal effect on the concepts of Physics at secondary school students.

H_o: Managing cognitive load on the academic performance of the secondary school students in the subject of physics has no significant difference based on gender.

Methodology

Research Design

A pre-test, post-test control group, quasi experimental design was applied with intervention of a full academic session (9 months) to determine the effect of CLT on the concepts of male and female Physics students at secondary level. The population of the study comprised of all secondary school students enrolled in public and private schools across Punjab.

Population and the Study Group

A total of 64 students from Grade 9 were selected as the study group for this experimental research. The study sample was equally split into two groups of 32 students each: one experimental and one control group. The selected participants were distributed in two homogenous groups depending on the pre-test score. Both groups included an equal number of boys and girls (16 boys and 16 girls per group). The experimental group received instruction based on Cognitive Load Theory strategies, while the control group was treated with the traditional teaching methods i.e. chalk and talk, question answers and written exercises.

Intervention

The 9 month intervention for the experimental group was designed based on (CLT) to optimize students’ working memory and enhance conceptual understanding in Physics. Instructional materials were simplified to reduce extraneous cognitive load by using clear visuals, minimizing redundant text, and eliminating irrelevant information. Intrinsic load was managed by sequencing content from simple to complex and ensuring that only essential information was introduced at each stage.

Germane cognitive load was promoted through the use of worked examples, self-explanation prompts, and schema construction activities. Dual coding techniques were applied by combining verbal explanations with relevant diagrams, while the modality effect was utilized by presenting auditory instructions alongside visual information instead of written text. Segmenting content into manageable chunks and providing pauses for reflection helped avoid information overload.

Furthermore, collaborative group discussions and scaffolded practice tasks were integrated to promote deeper learning and long-term memory retrieval. These strategies, supported by recent findings (Sweller et al., 2024; van Nooijen et al., 2024), were implemented consistently over a period of nine months to help students better process and retain complex Physics concepts.

Instrumentation

A self-constructed test was administered as the research instrument for this experimental study, functioning as both the pre-test and post-test. The test included 45 multiple-choice questions designed to assess students' conceptual understanding of Physics. It was applied to both the control and experimental groups to evaluate their academic performance before and after the intervention. To confirm the test's validity and reliability, item analysis was carried out following the procedures of Classical Test Theory (CTT).

In addition, the test was reviewed and validated by subject specialists. The reliability of the instrument was confirmed through pilot testing, which demonstrated a high level of internal consistency, with a Cronbach's Alpha coefficient of 0.853.

Control of Experimental Threats

To ensure the control of experimental threats in the present study, several measures were taken. Selection bias was minimized by using random assignment of students into control and experimental groups with equal representation of gender (16 boys and 16 girls in each group). Testing effects were controlled by using the same researcher-made conceptual test for both pretest and posttest across groups. Instrumentation threats were addressed by validating the test through subject specialists and establishing reliability through pilot testing, yielding a high Cronbach's Alpha value ($\alpha = 0.853$). Moreover, the teaching duration, instructional time, and classroom environment were kept consistent across both groups to reduce the impact of maturation, history, and environmental differences, ensuring that the observed differences could be attributed to the cognitive load intervention.

Data analysis

The scores obtained on the researcher-made test before and after the intervention for control and experimental groups were analyzed through both descriptive and inferential statistics. The pre-intervention scores and post tests were compared through an independent sample *t test.* Further, the gain score comparison was made by applying independent sample *t test* to see individual increase in the scores. Whereas, to see the gender differences in performance of students in both groups, an independent sample *t test* was calculated. Both inferential and descriptive tables and graphs are presented with interpretation. The level of significance was selected $P < 0.05$.

Results

Figure 1: Graph for Pre test of Control and Experimental Groups

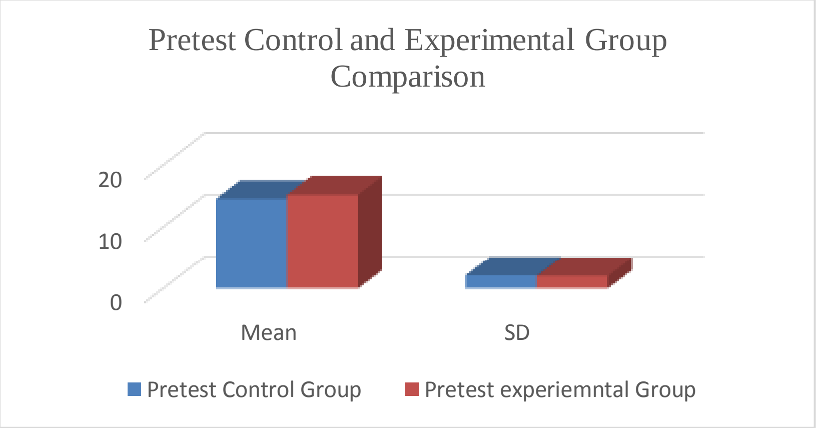

Table 1

Pre Intervention Difference in Intervention and Traditional Group in Physics Scores

		Group	N	Mean	Std. Deviation	Std. Error Mean
Physics Scores	Pretest	control group	32	14.59	2.138	.378
		experimental group	32	15.25	2.032	.359

Table 2

Pre intervention Comparison through t test

	F	Sig.	t	Df	Sig. (2-tail)	Mean Difference	Std. Error Difference
Physics pretest score	.150	.700	-1.259	62	.213	-.656	.521

In order to determine the homogeneity of both traditional and intervention groups, an independent sample *t test* was applied on the marks obtained on the MCQ test (45 items). Table 1 shows M= 14.59 for the control group with SD = 2.138 and M = 15.25 for the experimental group with SD = 2.032. Table 2 depicts the *t test* comparison which declared a minor insignificant difference with p =.700 and t (62) = -1.259. The critical value 0.05 decided that students in two groups had almost similar conceptual clarity in the subject of Physics before teaching through CLT.

Figure 2: Post test comparison of Control and Experimental Groups

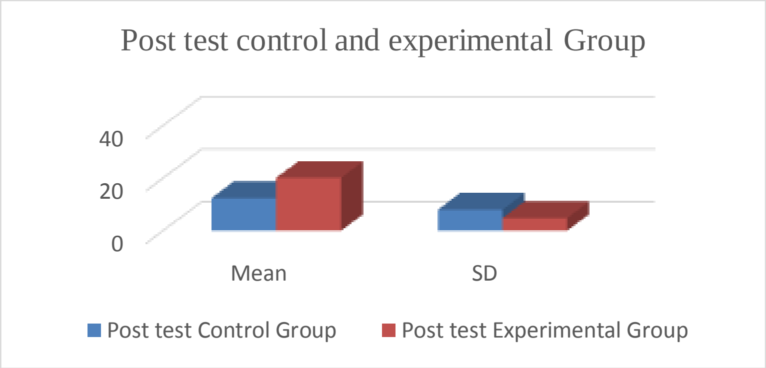

Table 3

Post Intervention Difference in Intervention and Traditional Group in Physics Scores

	Group	*N*	*Mean*	*Std. Deviation*	*Std. Error Mean*
Post intervention scores on Physics	*Control group*	*32*	*27.03*	*7.986*	*1.412*
	Experimental group	*32*	*35.59*	*5.381*	*.951*

Table 4

Post Intervention Comparison Through t test

	F	Sig.	T	df	Sig. (2-tail)	Mean Difference	Std. Error Difference
Physics posttest score	4.293	.042	-5.030	62	.000	-8.563	1.702

The null hypothesis, that cognitive load effects (i.e., split-attention effect, redundancy effect, expertise reversal effect, and modality effect) have no significant impact on secondary school students' comprehension of physics concepts was rejected. As per Table 3 and 4, the scores of intervention and traditional groups M = 27.03 with SD = 7.986 and M = 35.59 with SD = 5.381, revealed a clear increase in Physics concepts after intervention. These results were further strengthened by values obtained from the t value as t (62) = -5.030 whereas, p = .042 (two tailed). The critical p value, p .05 > .042, declared that the difference was substantial.

Figure 3: Gender Differences in Physics scores after intervention

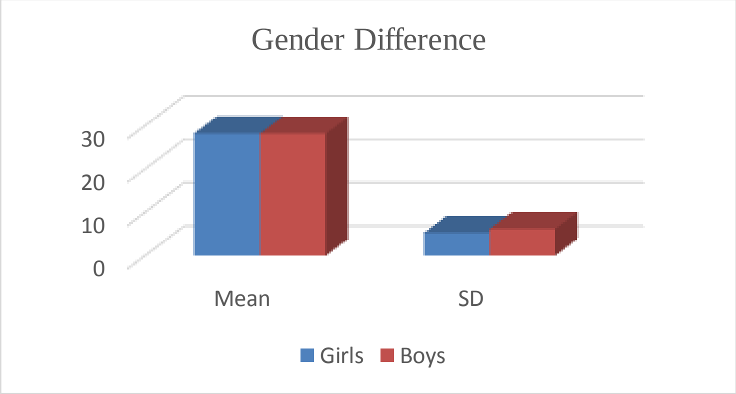

Table 5

Descriptives of Gender Differences in Scores of Physics

Gender	*N*	*Mean*	*Std. Deviation*	*Std. Error Mean*
Girls	*32*	*28.22*	*5.278*	*.933*
Boys	*32*	*28.13*	*6.179*	*1.092*

Table 6

Physics Scores Difference on Gender Basis Identified by t test

Boys and Girls Physics Scores	F	Sig.	t	df	Sig. (2-tail)	Mean Difference	Std. Error Difference
	1.183	.281	.065	62	.948	.094	1.436

Table 5 and 6 show gender differences in the intervention and control groups. The M = 28.22, for girls with SD = 5.28 and M = 28. 13 with SD =6.18 identified no clear difference in the concepts of Physics with reference to CLT instruction. Further, the *t test* also proved that the difference of boys' and girls' scores was minimal and insignificant with t (62) =.948 with p =.05 < .281. Thus, the hypothesis that boys and girls are similar in conceptual achievement in the subject of Physics was selected statistically.

Figure 4: Gain Score Comparison of Physics scores after intervention

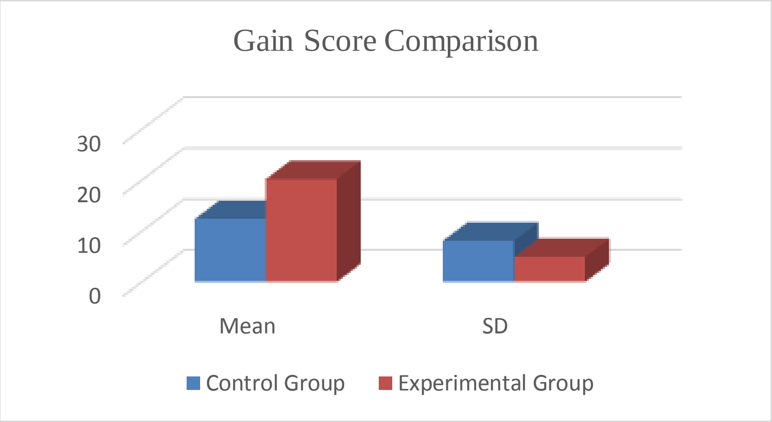

Table 8

Gain Score Difference in Control and Experimental Groups

	Group	N	Mean	Std. Deviation	Std. Error Mean
Gain Score	Control group	32	12.44	8.159	1.442
	experimental group	32	20.19	4.961	.877

Table 9

Gain Score Comparison of Control and Experimental Groups by t test

	F	Sig.	t	df	Sig. (2-tail)	Mean Difference	Std. Error Difference
Gain score	4.590	.036	-4.591	62	.000	-7.750	1.688

The final comparison was made to identify the differences of gain score of traditional and intervention group students. Table 8 and table 9 clearly manifest values of M = 12.44 with SD =8.16 for the traditional group and M = 20.19 with SD = 4.96 for the intervention group students. The calculation of *t test* determined that t (62) = -4.591 with p .05 < .036 was a significant difference with reference to CLT intervention. Therefore, it was evident that teaching through CLT and managing the cognitive load of Physics students was an effective strategy to enhance their learning.

Findings

1. Before starting intervention, there was no substantial difference in performance between the experimental and control groups; both displayed similar levels of understanding across all Physics topics.
2. Following the intervention, the experimental group showed a clear improvement, outperforming the control group in all areas of Physics covered in the study.

3. The instructional approach based on Cognitive Load Theory (CLT), including strategies like reducing split attention, avoiding redundancy, adjusting for learner expertise, and using multiple modalities, significantly enhanced students' comprehension of Physics concepts.
4. Gender did not play a role in moderating the intervention's effectiveness; both male and female students responded similarly to the CLT-based teaching methods, with no significant differences observed before or after the intervention.
5. The analysis of gain scores highlighted the significance of CLT, indicating that the CLT-informed intervention had a substantial positive influence on student learning outcomes.

Discussion and Conclusion

The current study was conducted to determine the effect of applying CLT on concept formation of Physics students. A cognitive management intervention was introduced to male and female secondary school students at public schools. The study supported previous research and provided evidence for all principles of CLT as; modality effect, redundancy effect, expertise reversal effect and split-attention effect for having positive influence on learning of Physics concepts. The students of the intervention group performed better than the traditional instruction group showing better concepts of Physics.

These results align with previous research. Wong et al. (2012) emphasized that animations presented in short segments are more effective than static graphics for transient knowledge. Similarly, the modality effect, favoring visual plus audio presentations over visual-only formats, is most effective with concise content. Luchini et al. (2015) confirmed the redundancy effect, showing that adding identical information in multiple formats (e.g., text and narration) can hinder comprehension for novice learners. Yeung (1999) also found that learner expertise modulates the impact of redundancy and split-attention effects. Gorjian and Kermanshahi (2017) concluded that demonstration methods enhance learning more effectively than text-based instruction, supporting the benefits of multimodal teaching.

The study also found no significant difference in performance between male and female students, both before and after the intervention. This is not compatible with earlier findings by Vasile et al. (2010), who reported gender differences in self-efficacy and working memory. In the present study, CLT-based strategies appeared equally effective for both genders, indicating their broad applicability in diverse classroom settings. Also, a significant difference in gain scores was observed between the groups, with the experimental group demonstrating greater improvement. This suggests a strong positive correlation between CLT-based instruction and students' academic gains in Physics. All findings by Cowan, 2021, Sweller, 2023, Zhong, Katkov and Tsodyks, 2024 about the functions of working memory were supported by the current study.

Recommendations

1. Teachers should integrate CLT strategies, such as reducing split attention, avoiding redundant information, and using visual and auditory modalities to enhance students' understanding of complex Physics concepts.
2. Training programs should be offered to help teachers design instruction that manages cognitive load effectively.
3. CLT- informed instructional methods may be applied across different levels and subjects.
4. Curriculum developers and policymakers should embed CLT principles in lesson planning and assessment frameworks.

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