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Instructional design considerations: Cognitive development and physics comprehension in secondary education

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Abstract—This paper discusses instructional design considerations for secondary school students' learning physics concepts, framed through cognitive development theories, particularly Jean Piaget's stages. It presents the relationship between age and physics comprehension, highlighting the overlap in cognitive development and students' challenges in learning physics concepts in secondary education. In comparison, older students demonstrate improved problem-solving skills and a deeper understanding of theoretical principles, while younger students rely on concrete experiences. The implications and recommendations were discussed in this paper.
Keywords: Cognitive development, Instructional design, Instructional strategies, Physics comprehension, Secondary education

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I. INTRODUCTION

RAPID advancements in understanding children's developmental and learning trajectories have opened avenues to foster more effective educational approaches. Leveraging these advancements requires integrating insights from various theories and philosophies of student development and the learning sciences (Darling-Hammond et al., 2019). This would involve connecting these insights with emerging knowledge of successful approaches to instructional designs. This paper, therefore, aims to contribute to the debate on instructional design considerations by examining the implications for school and classroom practices on the emerging consensus in the science of learning and development (SoLD) about the role of age and motivation on students' learning of concepts in physics. Key findings from the SoLD indicate that the brain and the growth of abilities for intricate mental processes are malleable and that brain development is experience-dependent (Cantor et al., 2018). This activation of neural pathways enables new types of performance and thought (Darling-Hammond et al., 2019). According to Liu et al. (2024), the brain and human faculties develop in interactive ways over the whole developmental spectrum, including the physical, cognitive, and affective domains, as a function of maturity. Understanding how these developmental processes unfold over time and interact in different contexts can contribute to more supportive designs for learning environments (Hénard & Roseveare, 2012; Swarat et al., 2017).

The ability of secondary school students to grasp physics concepts is significantly influenced by their age, chiefly due to the stages of cognitive development they experience during adolescence. As students mature, their cognitive capacities expand, enabling them to handle better abstract and hypothetical scenarios encountered in physics problems (Cerovac & Keane, 2024). By understanding the relationship between age and comprehension of abstract concepts in physics, educators can create more effective and inclusive learning environments that cater to the diverse needs of their students. This is underscored by considering students' cognitive readiness and motivational needs when designing physics instruction, advocating for differentiated instruction, and scaffolding to support students at various developmental stages.

Relationship between age and physics comprehension

Age significantly influences the ability of secondary school students to comprehend abstract physics concepts. This can be interpreted through Piaget's stages of cognitive development, which students experience during adolescence. Jean Piaget's theory of cognitive development delineates a progression from the concrete operational stage to the formal operational stage, typically occurring between the ages of 11 and 15. This progression coincides with the students' time in secondary school, where the ability to think abstractly becomes critical for understanding the complexities of physics (Smith et al., 2019). As students mature, their cognitive capacities expand, enabling them to handle better abstract and hypothetical scenarios encountered in physics problems.

Furthermore, Krsnik et al. (2002) investigated the cognitive development of secondary school physics students and their ability to engage in formal operational thinking, finding that a significant proportion of students had not yet fully transitioned to formal reasoning. Their study highlighted that cognitive level was a significant factor in comprehending concrete and formal physics concepts, with students at more advanced cognitive stages demonstrating improved proficiency in abstract reasoning. Similarly, Koenig et al. (2021) examined the impact of scientific reasoning abilities on physics comprehension, revealing that students with stronger formal reasoning skills exhibited higher conceptual understanding in physics problem-solving. Their findings indicate a correlation between cognitive development and the ability to handle abstract reasoning in physics. This reinforces the necessity of instructional strategies that support students' transition from concrete to formal operational thought. These studies support the observation that younger students often struggle with the abstract reasoning required for physics due to their ongoing cognitive development. In contrast, older students, typically in a more advanced stage, exhibit greater proficiency in abstract reasoning tasks.

Furthermore, age-influenced approaches to instruction are most effective for students. Instruction tailored to align with the cognitive readiness associated with various age groups can significantly impact learning outcomes. Johnson and Perkins (2018) assert that older students, armed with a higher ability for abstract reasoning, benefit greatly from pedagogical approaches that challenge their critical thinking and problem-solving skills. For younger students, instructional strategies involving hands-on experiments and tangible, real-world examples can facilitate a more concrete understanding of physics concepts during earlier cognitive stages (Swarat et al., 2017). Age also correlates with motivation and interest levels, which are pivotal in engaging students with physics material. Younger students may require stimulating and relatable contexts to capture their interest, as maintaining engagement in abstract topics can be challenging without a personal connection or practical relevance (Hénard & Roseveare, 2012). On the contrary, older students often have more developed interests and cognitive abilities, allowing them to explore the theoretical aspects of physics with greater enthusiasm due to their age. This suggests that age-appropriate instructional strategies should consider cognitive development and align with students' motivational needs and interests to optimise learning outcomes in physics.

The cognitive demands of physics concepts can vary significantly with age. Younger students may struggle with complex topics such as electricity and magnetism, which require a solid understanding of abstract principles and the ability to visualise non-visible phenomena (Mbonyiryivuze et al., 2018). On the other hand, older students are often better equipped to engage in these topics due to their enhanced cognitive capabilities, allowing them to tackle more advanced physics problems with greater ease. Overall, age shapes how secondary school students' approach and understand physics. This influence is mediated through the stages of cognitive development, responsiveness to age-specific instructional approaches, and varying levels of motivation and interest. Tailoring instructional strategies to consider extraneous factors such as age-related differences can foster better comprehension and appreciation of physics concepts among diverse student populations (Bigozzie et al., 2018).

Cognitive development and comprehension of physics concepts

Understanding how cognitive development affects students' comprehension of physics is crucial, particularly during the secondary school years when significant cognitive transitions occur. Jean Piaget's stages of cognitive development provide a foundational framework for understanding these changes. During the transition from the concrete operational stage to the formal operational stage, typically occurring between the ages of 11 and 15, students begin to develop the ability to think abstractly and logically, which is essential for grasping physics concepts (Aiello-Nicosia et al., 2020). This cognitive shift is particularly relevant in physics education, where students often engage with concepts that are not directly observable, such as forces, energy, and electromagnetic fields.

The progression to formal operational thinking involves an enhanced ability to handle abstract concepts and hypothetical reasoning, which are critical in physics. Piaget's theory suggests that younger students, often still in the concrete operational stage, might struggle with abstract physics concepts, relying more on tangible experiences (Gibbings & Sefton, 2012). This difference in cognitive development stages could explain variations in how students of different ages understand and learn physics. For instance, younger students may excel in hands-on experiments but find applying their observations to theoretical frameworks challenging. In comparison, older students can integrate theoretical knowledge with practical applications more effectively (Liu & Sun, 2019). Some essential alignments of cognitive development and major features of physics are highlighted herein:

Abstract thinking

Abstract thinking is central to physics education, allowing students to explore key concepts such as forces, energy, and other phenomena that are not directly observable (Sabí'n, 2024). As students develop cognitively, their capacity for abstract thought improves, enabling them to engage in mental modelling and thought experiments, as seen in challenging concepts like Special Relativity (Gibbings & Sefton, 2012). Research indicates that students who have reached the formal operational stage can better understand and manipulate abstract representations of physical phenomena, which is crucial for solving complex physics problems (Liu & Sun, 2019). For example, students in this stage can visualise electric fields and forces acting at a distance, which is essential for understanding concepts such as Coulomb's law and electric potential. Moreover, abstract thinking enables students to move beyond rote memorisation, which may not always benefit physics learning, towards conceptual reasoning, fostering a deeper understanding of the principles that govern physical systems.

Problem-solving skills

The development of problem-solving skills is intricately connected to cognitive growth, which unfolds as students' progress through their educational journey. As they mature, students become increasingly adept at utilising logical reasoning, pinpointing variables, and addressing complex problems—competencies crucial for success in physics. Research studies have highlighted the significant influence of cognitive factors on students' capacity to employ proportional reasoning, an essential skill when tackling physics problems (Akatugba & Wallace, 2019). For instance, older students often demonstrate a greater tendency to adopt systematic and methodical approaches to problem-solving. This might involve decomposing intricate questions into smaller, more manageable components. This strategy promotes clarity and empowers them to confront and resolve challenging physics tasks with confidence and efficacy.

Working memory

Working memory capacity plays a significant role in learning physics. Holding and manipulating information is essential for solving equations and understanding physical systems. Research indicates that working memory, which develops with age, is crucial for integrating new information with prior knowledge, facilitating a deeper understanding (Akatugba & Wallace, 2019). Challenges related to working memory can hinder students' progress, particularly when they attempt to solve multi-step physics problems. For instance, students with limited working memory may struggle to keep track of multiple variables in a physics problem, resulting in errors and misconceptions about the concepts. This indicates that working memory is influenced by age; as students grow older, their working memory capacity increases, aiding their ability to tackle complex tasks.

Cognitive development overlaps and challenges in physics education

Addressing age differences in physics education presents several challenges and limitations that educators must navigate to enhance student learning effectively. One significant challenge is accurately distinguishing cognitive development stages and aligning them strictly according to age. Cognitive skills may advance not purely by age but through complex interactions between cognitive ability and educational context. For instance, research has shown that students' reasoning skills can develop variably based on the learning environment and instructional methods rather than strictly following age-related milestones (Akatugba & Wallace, 2019). The following are contextual factors that overlap with cognitive development and negate the influence of age:

Socio-cultural influences

Socio-cultural factors significantly influence age-related cognitive development, affecting students' reasoning skills. The differences in cognitive development can vary greatly based on cultural norms and educational practices, making it challenging to apply universally effective teaching strategies (Akatugba & Wallace, 2019). For instance, students from diverse cultural backgrounds may have different experiences with collaborative learning, which can impact their engagement with physics content. This underscores the importance of educators considering socio-cultural contexts when designing instructional strategies for diverse classrooms (Cheryan et al., 2017).

Implementing culturally responsive learning incorporating locally relevant examples and real-world applications can help bridge these gaps and improve students' conceptual understanding. Moreover, fostering an inclusive learning environment that recognises and values diverse perspectives is essential.

Qualitative methodological constraints

Qualitative studies provide deep insights into student reasoning processes but may not effectively generalise across different age groups due to small sample sizes and specific contextual influences. This limitation can hinder broad claims about age-specific differences in physics understanding (Kim & Lee, 2020). For instance, while qualitative insights can reveal how younger students conceptualise electricity, the findings may not represent older students' experiences, thus complicating the development of age-appropriate instructional strategies. The absence of large-scale comparative studies makes it difficult to identify consistent patterns in cognitive development across different student populations. Additionally, the lack of quantitative validation in many qualitative studies restricts their applicability in designing evidence-based curriculum adjustments. Therefore, a mixed-methods approach integrating qualitative depth with quantitative breadth may provide a more comprehensive understanding of age-related variations in physics learning.

Lack of direct research focus

There is a scarcity of studies that directly focus on age as a primary variable affecting physics education within qualitative frameworks. This gap suggests limitations in the research community's current ability to provide insights or confirm assumptions about the impact of age on physics learning through in-depth analyses (Gutiérrez et al., 2023). Without robust research focusing on age-related differences, educators may struggle to implement effective strategies tailored to their students' cognitive development. The absence of age-specific investigations also limits the ability to assess how instructional interventions should be adjusted to accommodate varying developmental stages. Furthermore, most existing studies focus on broad pedagogical approaches rather than examining how students of different age groups respond to specific teaching methods in physics. Addressing this research gap through longitudinal and comparative studies could provide valuable data for refining instructional practices and improving learning outcomes across different age cohorts.

Educational system variability

Variability in educational systems complicates the direct application of findings across global contexts. The studies reviewed, such as those by Akatugba and Wallace (2019), underscore how contextual factors within specific educational systems can diverge widely, thus challenging the universal application of age-specific educational strategies. For example, one country's curriculum and teaching practices may not align with those of another, making it difficult to generalise findings about age-related cognitive development across different educational environments (Liu & Sun, 2019). Additionally, differences in educator training, resource availability, school supervision, type of school, and assessment methods further contribute to inconsistencies in how students develop physics comprehension across regions.

II. EDUCATIONAL IMPLICATIONS

Given the influence of cognitive development on physics learning, it is essential to tailor instructional methods to students' developmental stages. For younger students, educational strategies that emphasise concrete examples and hands-on activities can be beneficial, helping them to bridge the gap between concrete and abstract thinking (Akatugba & Wallace, 2019). For older students, fostering an environment that encourages logical reasoning, hypothesis testing, and critical analysis can enhance their conceptual understanding. Additionally, understanding that cognitive development varies among students, even within the same age group, is crucial for educators. Differentiated instruction can address individual needs and promote effective learning. For example, educators can challenge older students with complex problem-solving exercises that call for higher order thinking skills while offering scaffolding to younger students to assist them in making the shift from concrete to abstract reasoning. Educators may design more inclusive and productive learning environments that meet the various requirements of their students by acknowledging the significance of cognitive development and how it affects physics learning.

III. CONCLUSION

The relationship between age and learning physics is a complex interplay of cognitive development, instructional strategies, and motivational factors. As secondary school students progress through adolescence, their cognitive abilities evolve from concrete operational to formal operational stages, as outlined by Jean Piaget's theory of cognitive development (Miller & Aloise-Young, 2018). This transition significantly impacts their understanding of abstract physics concepts. Younger students, often still in the concrete operational stage, may struggle with the abstract reasoning required for physics, relying more on tangible experiences (Swarat et al., 2017). In contrast, older students in the formal operational stage better manage abstract concepts and hypothetical scenarios in physics problems. This age-related difference in cognitive development highlights the need for tailored instructional strategies to optimise learning outcomes.

Scaffolding, differentiated instruction, collaborative learning environments, and age-responsive technological integration are effective approaches for addressing the diverse cognitive needs of students based on their developmental stage (Hénard & Roseveare, 2012). By providing guided support, catering to individual learning needs, fostering peer collaboration, and incorporating interactive technologies, educators can create inclusive and effective learning environments that cater to students of all ages. However, challenges in accurately distinguishing cognitive development stages, socio-cultural influences, methodological constraints, and variability in educational systems complicate the direct application of age-specific instructional strategies (Neumann et al., 2002). Ongoing research and a deeper understanding of the interplay between age, cognitive development, and physics learning are necessary to develop more effective and inclusive educational practices.

In conclusion, age plays a significant role in shaping secondary school students' approach and understanding physics. Educators can foster a deeper appreciation and learn physics concepts among diverse student populations by recognising the impact of cognitive development stages and implementing tailored instructional strategies. As research in this field continues to evolve, the educational community can work towards creating more age-responsive and inclusive physics education.

IV. RECOMMENDATIONS

As students' progress through secondary education, their cognitive abilities transition from concrete to formal operational stages, necessitating instructional strategies that align with their developmental needs, particularly in physics education, where abstract reasoning is essential (Inhelder & Piaget, 1958). Scaffolding, grounded in Vygotsky's Zone of Proximal Development, provides temporary support to help students grasp complex physics concepts, using tools like physical models and simulations to visualise abstract ideas (Chen et al., 2019; Kim & Lee, 2020). Differentiated instruction accommodates diverse learning needs by tailoring teaching methods to students' cognitive readiness, with younger students benefiting from contextual learning while older students engage in experiential projects that deepen conceptual understanding (Harper et al., 2020; Gutiérrez et al., 2023). Collaborative learning fosters cognitive development by encouraging peer interaction, where younger students refine their reasoning skills and older students strengthen their understanding through debate and cooperative problem-solving (Smith & Wiser, 2021;

Bian et al., 2018). Additionally, guided inquiry and Socratic questioning enhance higher-order thinking, prompting students to ask questions, hypothesise, and engage critically with physics content (Lee, 2021). Age-responsive technological integration, such as virtual labs and simulations, further supports personalised learning by adapting to students' cognitive readiness and providing interactive visualisation of physics phenomena (Kimberly & Arthur, 2019). By combining scaffolding, differentiated instruction, collaborative learning, and technology-driven strategies, educators can create inclusive learning environments that foster students' ability to grasp abstract physics concepts, overcome learning challenges, and achieve deeper understanding.

V. CONFLICTS OF INTEREST

There are no conflicts of interest.

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