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Integrating Energy Literacy and Computational Thinking in Secondary Education: A Rasch-Based Analysis to Support Game-Based Physics Learning

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Abstract: The urgency of global energy and environmental challenges underscores the importance of integrating energy literacy and computational thinking (CT) in secondary science education. This study investigates the impact of a digital game-based learning intervention aimed at enhancing these competencies within the physics curriculum. Using a static-group pretest-posttest design, 72 senior high school students were divided into an experimental group receiving game-based instruction and a control group experiencing conventional teaching. A 20-item multiple-choice test was developed and analyzed using the Rasch model. Findings revealed that the experimental group achieved significantly higher post-test ability scores (1.66 logits) than the control group (0.97 logits), indicating a shift toward higher ability levels. Students exposed to the game demonstrated stronger capabilities in integrating conceptual understanding of energy systems with systematic problem-solving strategies, as well as in tasks requiring advanced reasoning, pattern recognition, and abstraction. However, some high-level competencies—particularly those involving the synthesis of conceptual knowledge with algorithmic thinking—remained challenging. The results suggest that digital game-based learning can effectively foster deeper, multidimensional competencies in physics education, yet further refinements in game design, especially in scaffolding complex problem scenarios and promoting structured reflection, are essential to maximize its educational impact.

Keywords: Computational thinking; Energy literacy, Digital game-based learning; Physics education; Rasch model; Renewable energy

Introduction

The global climate crisis and the urgent need for an energy transition toward renewable sources have become pressing issues for many countries, including Indonesia. The reliance on fossil fuels and the resulting increase in greenhouse gas emissions have exacerbated environmental sustainability problems on both national and global scales (C. Liu & Liu, 2023). Within formal education, energy literacy has emerged as a crucial foundation for fostering awareness and responsible action among youth concerning energy and environmental issues (Appiah et al., 2023; Lowan-Trudeau & Fowler, 2022; Odden & Zwickl, 2025). Conceptually, energy literacy encompasses knowledge of energy sources, usage, and their environmental and social impacts (Derek Gladwing, 2023; Santillán & Cedano, 2023; Yusup et al., 2017). Simultaneously, computational thinking (CT) is a key 21st-century competency that equips students with the ability to solve problems logically and systematically (Nouri et al., 2020). Computational thinking includes problem decomposition, pattern recognition, abstraction, and algorithm design (Orban & Teeling-Smith, 2020; Wing, 2006). The combination of these competencies is believed to enhance students' decision-making regarding

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renewable energy use, particularly through interactive media such as games. This conceptual framework underpins the quantitative study conducted to measure the depth of both competencies within a student population. Integrating energy literacy and computational thinking through innovative learning media is essential in the physics curriculum (Khasanah et al., 2025).

Although efforts to improve energy literacy and computational thinking have been implemented independently, a gap remains in their integrated application at the secondary education level. Usman et al. (2021) reported that Indonesian middle school students exhibited moderate levels of energy literacy, with particularly low scores in the cognitive domain (Dewi et al., 2024). Meanwhile, meta-analytic studies indicate that game-based learning effectively enhances computational thinking (Jingsi Ma , Yi Zhang , Zhifang Zhu, 2023; Lu et al., 2023; Pan et al., 2024; X. Wang et al., 2023) though little focus has been given to its application in physics and energy contexts (M. Wang & Zheng, 2021; Zeng et al., 2020). Thus, this study aims to fill this gap by exploring the levels of energy literacy and computational thinking among high school students as a foundation for developing game-based physics learning media.

This study responds to that gap by investigating student competencies through the dual lens of energy and computation, particularly within the context of physics instruction. The integration of these two domains is operationalized through an assessment framework and supported by a digital game-based learning intervention. Preliminary observations indicate that students struggle with system-level energy reasoning and algorithmic planning—suggesting a need for targeted instructional designs that address these combined competencies in accessible, engaging ways.

Accordingly, this research aims to examine the extent to which a digital physics game can support the development of both energy literacy and computational thinking, as measured through a Rasch-based analysis of student responses. The study also explores item-level functioning through DIF to identify which types of competencies are most impacted by the game environment.

Method

Research Design

This study employed a static-group pretest-posttest design, involving two intact classes assigned as the experimental and control groups, following Figure 1 (Fraenkel et al., 2012), from tenth graders in one public senior high school in Musi Banyuasin, South Sumatra. The experimental group (n=36) received an instructional intervention using a digital game previously developed by the researchers (first author and team), while the control group (n=36) underwent conventional physics instruction. The game simulated real-life scenarios involving renewable energy choices, system planning, device efficiency management, and algorithmic decision sequences. Players were prompted to optimize energy usage while navigating trade-offs and feedback loops, reinforcing both procedural reasoning and socio-environmental understanding. Students' activities in the experiment group are depicted in Figure 2.

Experiment group	O 20 MC items pretest	X Treatment: Digital game-based learning	O 20 MC items Posttest
Control group	O 20 MC items pretest		O 20 MC items Posttest

Figure 1. The static-group pretest-posttest design used in this research

Figure 2. Students played a game in the experiment group

Instrument

The data was collected through test instruments administered before and after the treatment phase. The data comprised students' responses to 20 multiple-choice test items, scored dichotomously, where 0 indicated a wrong response and 1 indicated a right one. The test was constructed by the researchers based on two integrated conceptual frameworks: energy literacy (Santillán & Cedano, 2023; Yusup et al., 2017) and computational thinking (Wing, 2006)). Each item was mapped to one of eleven integrated competencies, including ethical reasoning and abstraction (items 1, 20), energy source identification and pattern recognition (items 2–3), system decomposition (items 5, 15–17), and algorithmic problem-solving (items 7–8, 11, 14), among others. The instrument underwent content validation through expert judgment to ensure alignment with curriculum standards and research constructs.

Validation using data from 40 participants who responded to a 20-item multiple-choice test, the instrument had acceptable psychometric properties. All items fell within acceptable fit statistics ranges, with infit and outfit mean square (mnsq) values between 0.5 and 1.5, indicating that item responses were consistent with the expectations of the Rasch model (Bond & Fox, 2015; Boone et al., 2014). No item showed evidence of statistical misfit, which suggests that each item contributed meaningfully to the underlying construct being measured.

The reliability coefficients further supported the instrument's internal consistency. Person reliability was 0.77 (Cronbach Alpha .79, SEM = 1.76), indicating the instrument's ability to distinguish among individuals with different ability levels. Item reliability was 0,88, suggesting that the items provided a sufficiently broad range of difficulty and that the test could reliably rank-order participants across the latent trait continuum.

Unidimensionality was confirmed through principal component analysis (PCA) of residuals. The first contrast eigenvalue was below 2.0, and the percentage of variance explained by the Rasch dimension exceeded 40%, both of which support the assumption that the instrument primarily measured a single underlying trait.

Data Analysis

Data was analyzed using the Rasch model, implemented through Winsteps software (Linacre, 2016). This model was chosen for its ability to transform ordinal raw scores into interval measures expressed in logits (log odds unit), and for its robustness in evaluating the psychometric quality of both items and person measures. Logit is the scale unit that results when the Rasch model is used to transform raw scores obtained from ordinal data to log odds ratios on the real number line (Bond & Fox, 2015). The analysis included infit and outfit mean square statistics, reliability indices for both items and persons, item difficulty calibration, person ability estimation, principal component analysis (PCA) of residuals to verify unidimensionality, and an item/person or variable map (called a Wright map).

Result and Discussion

Comparison of post-test performance between groups

The analysis presented in this section is based on post-test data. Before the intervention, a pre-test was conducted to ensure equivalence between the experimental and control groups. The results of the pre-test indicated that there was no statistically significant difference in the mean scores of the two groups, thereby confirming their comparability at the outset of the study. The result of the post-test is presented in Table 1.

The Rasch analysis of student posttest scores, as shown in Table 1, revealed a substantial difference in ability levels between the experimental and control groups. These scores, expressed in logits, offer an interpretable scale where a value of 0.00 logits represents the average difficulty of the test items.

Table 1. Group statistics of post-test data

Group	N	Mean (logit)	Std. Deviation	Std. Error Mean	Sig. p
Experiment	36	1.66	0.48	0.08	<.001
Control	36	0.97	0.85	0.14	

In this study, the experimental group demonstrated a mean ability of 1.66 logits, while the control group averaged 0.97 logits, yielding a gap of 0.69 logits. This difference clearly places the experimental group well above the item difficulty average, while the control group, although above 0.00 logits, remains at a relatively moderate proficiency level.

From a measurement perspective, such a gap is not only educationally meaningful but also statistically robust. According to Linacre (2025), a difference of just 0.15 logits can be considered statistically significant using a two-sided 0.05-level t-test, assuming standard errors of approximately 0.05 logits, which generally correspond to around 250 dichotomous responses per person or item. In our case, even with larger standard errors (0.08 for the experimental group and 0.14 for the control group), the magnitude of the 0.69-logit difference greatly exceeds the minimum threshold for significance. This suggests that the digital game-based instructional approach was not only effective in raising scores but also moved students into higher ability categories, confirming the educational impact of the intervention. These findings are consistent with previous studies (Febianti & Sukmawati, 2024; Gui et al., 2023; Z. Y. Liu et al., 2020; Rahmatania et al., 2024; Schrand, 2008; L. H. Wang et al., 2022) that reported significant learning gains and improved motivation through well-designed game-based learning environments.

The higher logit scores indicate that students in the experimental group had a substantially greater probability of answering both average and more difficult items correctly. This is particularly important because the test was designed to measure integrated competencies in energy literacy and computational thinking, two domains that require both conceptual understanding and procedural reasoning. The game-based learning environment, by embedding problem-solving (Rosydiana et al., 2023; A. Usman et al., 2024) challenges into interactive simulations, likely provided students with opportunities to repeatedly practice decomposition, pattern recognition, and algorithm design—core skills in computational thinking (Almujaddid et al., 2025; Pangsuma et al., 2025).

These quantitative differences reflect the potential instructional value of the game-based intervention, particularly in promoting engagement with interdisciplinary content areas that combine energy literacy and computational thinking. However, aggregate scores alone do not reveal which specific competencies were most affected. To explore this further, the study turned to Rasch person–item mapping and item-level DIF analysis.

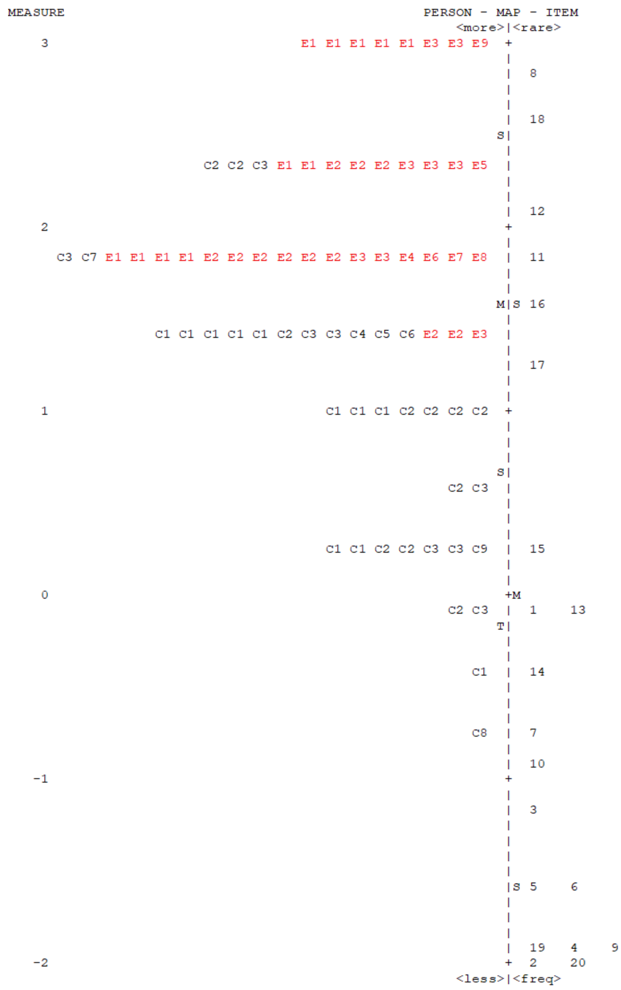

Figure 3. Wright map of students' ability and items' difficulty.

Ability Distribution and Competency Alignment: Insights from the Wright Map

Figure 3 shows the Wright map of students' responses on the test instrument. The Wright map—also known as a person–item map—is a key visual output in Rasch measurement analysis, displaying the estimated distribution of person abilities and item difficulties along a shared linear scale measured in logits. This dual-axis representation allows for intuitive comparisons between the competency levels of individuals and the relative difficulty of the test items they encounter.

In the Wright Map, the vertical axis represents the logit scale, where higher values indicate higher levels of the latent trait being measured—in this case, integrated energy literacy and computational thinking ability. The scale is symmetrical and standardized, annotated with letters such as M, S, and T to signify key statistical reference points. M (mean) indicates the average value for either persons or items, depending on the side of the map. S (standard deviation) marks one standard deviation from the mean. T (two standard deviations) marks two standard deviations from the mean.

The left side of the vertical axis typically displays person measures—each line or symbol representing an individual student's estimated ability. Those located toward the top of the scale have the highest ability estimates, indicating a high probability of correctly answering items across a wide range of difficulty. Conversely, students plotted near the bottom have lower ability estimates and are expected to perform well only on the least difficult items.

On the right side of the axis, item difficulties are plotted. Items higher on the scale are considered more difficult, requiring greater ability to answer correctly, while items near the bottom are easier and can be correctly answered even by individuals with lower estimated abilities. The vertical alignment allows for a direct comparison: when a person and an item appear at the same horizontal level, the Rasch model predicts that the person has a 50% probability of responding correctly to that item. If a person is located above an item, the probability of a correct response is greater than 50%, while if the person is located below an item, the probability falls below 50%.

In this study, each of the 20 test items was developed to reflect specific dimensions of an integrated competency framework that combines energy literacy and computational thinking. While it may be tempting to directly associate individual logit scores with mastery of specific competencies based on item numbers, such interpretation demands caution. The alignment between person ability estimates and item difficulty parameters reflects probabilistic tendencies, not deterministic mastery of individual constructs—especially when each competency is represented by only one or two items.

Nonetheless, patterns emerge in the data that reflect broader differences in the depth and complexity of competencies that different groups of students are likely to engage with. Figure 2 shows that students in the experimental group were more evenly distributed along the ability continuum, with a significant portion surpassing the average item difficulty, while the control group was more clustered in the lower logit regions. Students in the experimental group (marked in red font, initialed as E) consistently occupy higher positions on the Wright Map, with a subset reaching beyond 1.87 logits. This positioning indicates a strong likelihood of responding correctly not only to items of average difficulty but also to those calibrated as more challenging.

Several items were positioned well above the mean person logit for both groups, indicating competencies that were systematically more difficult. These included Items 8, 18, 12, and 11, which required advanced reasoning such as algorithmic planning, ethical evaluation of procedures, and interpretation of data patterns across device systems. While students in the experimental group showed better overall performance, many of the high-complexity items remained challenging even for them—underscoring the need for more explicit support within the game environment for multistep, abstract, and data-driven reasoning processes.

Conversely, students from the control group (marked in black font, initialed as C) tend to cluster below 1.42 logits, indicating a limited probability of success on items beyond the average difficulty level. Items located below the mean person logit, such as Items 1, 2, and 6, were successfully answered by most students, reflecting competencies situated at lower levels of cognitive complexity. Item 1, which asked students to identify the most appropriate reason for reducing the use of fossil fuels, assessed basic environmental awareness—specifically, the link between fossil fuel consumption and carbon dioxide emissions. The high success rate on this item across both groups suggests that such knowledge is relatively well-established, likely due to its presence in formal curriculum and widespread public discourse on climate change. Nevertheless, the alignment of this item with real-world concerns underscores its relevance in foundational energy literacy, particularly in the domain of impact evaluation.

Item 2, although similar in complexity, required students to distinguish between renewable and nonrenewable sources by identifying a characteristic feature—namely, whether the resource can be replenished naturally. While the conceptual load of the item was not high, it did require the ability to generalize a definitional rule across categories. Student responses indicated generally high comprehension, with no significant performance gap, though there was a slight advantage for the experimental group, possibly due to reinforcement through classification activities embedded in the game.

Most notably, Item 6, which asked about the broader strategic rationale behind transitioning to renewable energy, required students to connect energy choices with policy-level implications, such as reducing reliance on fossil fuels. This item, although positioned at a similar difficulty level, tapped into more integrative reasoning than Items 1 and 2. The experimental group outperformed the control group on this item, suggesting that the digital game's design effectively communicated the strategic dimensions of energy transition through its scenario-based narrative structure. Taken together, performance on these three items reflects a solid grasp of fundamental energy concepts among students, while highlighting the game's unique affordance in reinforcing deeper contextual understanding.

It is important to clarify that the Wright Map provides inference based on aggregate behavior, not diagnostic claims about individual competency profiles. As Bond and Fox (2015) emphasize, person measures represent the interaction between a learner's latent trait and the total set of item difficulties, not a reflection of specific domain mastery unless the instrument is specifically scaled and validated for such fine-grained interpretation.

Still, the broader implications of this distribution are significant. Students in the experimental group were not only more likely to succeed overall, but were also more likely to encounter, interact with, and respond correctly to items aligned with higher cognitive complexity. In turn, this suggests that the digital game-based learning intervention did more than increase test scores—it expanded access to deeper dimensions of learning. This is consistent with the theoretical perspective that well-designed games can support learning across multiple cognitive levels, especially when grounded in curricular frameworks and competency-based design (Alfaro-Ponce et al., 2023; Plass et al., 2015). This supports prior research suggesting that well-structured game-based interventions can foster engagement with complex competencies, particularly when embedded in contextual and interactive environments (Emihovich, 2024).

Instructional impact and gaps: Analysis of differential item functioning (DIF)

The Differential Item Functioning (DIF) analysis provided further insight into how specific test items functioned across instructional contexts, offering empirical support to explain which competencies were more strongly shaped by the digital game-based intervention. While the Rasch model established that students in the experimental group generally performed better across the instrument, the DIF analysis revealed meaningful contrasts at the item level, highlighting not only the overall advantage but also where and how it manifested, as well as where it was absent or even reversed.

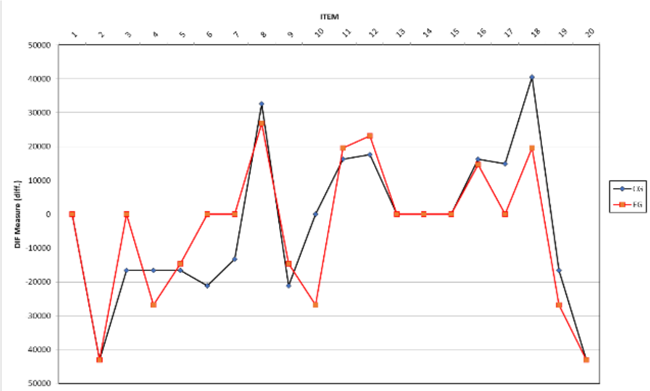

Figure 4. Person DIF Plot: Comparison between the experiment group (EG, red) and the control group (CG, black) across the instrument

Among the items in Figure 4 that demonstrated a positive DIF, indicating a relative advantage for the experimental group, were Item 3 and Item 6. Item 3, which required students to identify the environmental risks associated with nuclear energy, appears to have been more accessible to students who used the game. This suggests that the game effectively contextualized abstract risks into interactive scenarios or narratives, allowing students to understand the consequences of energy decisions in a way that extended beyond textbook descriptions. Similarly, Item 6, which addressed the benefits of transitioning away from fossil fuels, favored the experimental group, pointing to the game's capacity to convey socio-strategic dimensions of energy use through its simulations. These items reflect competencies that are conceptually situated and context-dependent—precisely the kinds of knowledge structures that immersive digital environments are well-suited to support. These findings align with prior research indicating that simulation and game environments enhance conceptual learning and socio-environmental reasoning when such elements are embedded meaningfully in gameplay (Muenz et al., 2023)

In contrast, the analysis identified a set of items, namely Item 4, Item 10, Item 17, and Item 18, that displayed negative DIF, meaning that students in the control group performed better despite their lower overall ability levels. Item 4, a straightforward definitional item regarding the classification of solar energy, may have been more effectively reinforced through explicit instruction in the traditional classroom, highlighting a possible gap in how factual content was integrated into the game. Item 10, which required understanding of energy efficiency as a function of input-output comparison, likely demanded a conceptual structure or mathematical framing that was either implicit or insufficiently emphasized in the game mechanics. This pattern is also evident in Items 17 and 18, both of which required students to analyze usage patterns and interpret data across devices or periods.

Despite the game's engagement with energy systems, these types of analytical reasoning tasks may not have been fully developed within the game, especially if students were not prompted to make abstract inferences from structured data sources like tables or graphs. This suggests that students' ability to abstract and construct generalized models from specific instances or data patterns remains an area of relative weakness. Prior studies have similarly reported that while game-based learning can effectively promote conceptual understanding and engagement, it does not always sufficiently cultivate abstraction skills—particularly those related to modeling—unless explicitly scaffolded through targeted instructional strategies (Handayani et al., 2022; Karogal et al., 2025)

The DIF analysis, therefore, does not contradict the positive findings observed through Rasch analysis; rather, it elaborates them. It shows that the digital game-based intervention was particularly effective in supporting students' development of conceptual understanding in complex, context-sensitive domains of energy literacy, but less effective in fostering competencies tied to factual retention and formal data analysis. These insights are critical for informing future development of the game. They suggest that targeted refinement, such as integrating more explicit scaffolds for quantitative reasoning and diagnostic interpretation, is necessary to extend the instructional impact of the game across the full spectrum of intended learning outcomes.

Synthesis: Advancing the integration of energy literacy and computational thinking through game-based learning

The multi-layered analysis in this study provides strong evidence that integrating energy literacy and computational thinking through digital game-based learning can significantly improve students' cognitive engagement and performance in secondary education. The Rasch model confirmed a general advantage in ability distribution among students exposed to the game, while DIF analysis clarified that this advantage is most evident in context-rich, affective, and strategic reasoning domains, such as understanding energy trade-offs and sustainability implications.

The analysis of student response data using the Rasch model revealed clear differences in the distribution of abilities between the experimental and control groups. Students who engaged with the digital game demonstrated higher average ability levels and a broader distribution across the competency spectrum. The Wright Map indicated that a greater proportion of students in the experimental group achieved person measures above the item difficulty mean, suggesting successful engagement with mid- to high-complexity competencies.

Despite these gains, several items positioned above the average person's ability level remained challenging for most students, indicating persistent difficulties with advanced integrative competencies. This includes competencies requiring multi-step reasoning, system-level abstraction, and data-based inference. Conversely, lower-difficulty items were generally well mastered, reflecting success in foundational understanding and procedural application.

However, the analysis also revealed critical gaps. The game-based approach did not sufficiently support competencies that require precise factual recall or analytical abstraction from textual data representations, such as interpreting usage tables or calculating efficiency. This suggests that game design must be complemented with deliberate instructional scaffolding—including feedback loops, embedded data tasks, and reflective prompts—to reach the full range of targeted competencies, as revealed by Muenz et al. (2023).

These findings suggest that while the digital game supported measurable learning gains in energy literacy and computational thinking, certain cognitive domains—particularly those involving abstract planning and complex decision-making—require further instructional support within the game design. The Rasch-based analysis thus confirms both the impact of the intervention and the areas where refinement is needed to extend competency development to more advanced levels.

Overall, this study reinforces the value of game-based learning for physics education while also demonstrating that its effectiveness depends on careful alignment between instructional mechanics and cognitive demands. As such, the Rasch and DIF-informed diagnostic approach employed here provides not only empirical validation of the intervention's strengths but also a roadmap for its iterative improvement.

Conclusion

This study demonstrates that integrating energy literacy and computational thinking through digital game-based learning can substantially enhance senior high school students' cognitive performance in physics education. Compared to the control group, students in the experimental group demonstrated stronger abilities in integrating conceptual understanding of energy systems with systematic problem-solving strategies. Game-based learning was particularly effective in enabling students to engage with tasks requiring higher levels of reasoning, pattern recognition, and abstraction, which are essential for addressing complex physics problems. Despite these gains, the findings also reveal that some advanced competencies, particularly those that require the synthesis of conceptual knowledge with algorithmic thinking, remain challenging for many students. This suggests that while digital games can successfully enhance engagement and conceptual integration, further refinements in game design—particularly in scaffolding complex problem scenarios—are needed to maximize learning outcomes. Overall, the integration of digital game-based learning provides a promising pathway for supporting deeper, multidimensional competencies in high school physics education.

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Author Contributions

Conceptualization, M.Y. and S.M.S; methodology, M.Y., S.M.S; software, M.Y.; validation, M.Y., M.R.H.; formal analysis, M.Y.; investigation, M.R.H; resources, S.M.S., M.R.H.; data curation, M.Y., S.M.S.; writing—original draft preparation, M. Y., M.R.H; writing—review and editing, M.Y., M.R.H; visualization, M.Y.; supervision, S.M.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest

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