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Kinaesthetic methodology as a tool for fostering embodied conceptual understanding of physics

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Abstract. The problem of overreliance of contemporary physical education on visual methods leads to a neglect of critically important kinaesthetic mental images necessary for deep learning of the natural sciences, in particular physics. The study was grounded in Embodied Cognition Theory and the tenet that core physical concepts are rooted in the primary sensory schema of "effort-resistance-motion". The purpose of the study was to develop and experimentally verify a kinaesthetic methodology (grounded in embodied cognition) to enhance embodied understanding and bridge the phenomenological gap in students during physics instruction. The research was conducted as a two-year quasi-experimental project in a specialised high school. An experimental group ($n = 18$) instructed using the kinaesthetic methodology and a control group ($n = 22$) following the conventional curriculum were established. Methodology integrated three types of kinaesthetic exercises (tactile-motor, spatial-locomotive, and role-play simulations) with the use of the mobile application Phyphox for the immediate objectification of subjective bodily sensations into objective physical data. Effectiveness was assessed using the embodied conceptual understanding assessment scale. The results of the statistical analysis (Student's t-test) convincingly confirmed the hypothesis: the mean gain score in the experimental group ($\overline{X}_1 = 7.17$) was statistically significantly higher compared to the control group ($\overline{X}_2 = 5.00$), with the calculated $t \approx 7.89$ indicating a strong effect size. This disparity was particularly evident in the embodied-kinesthetic component of the embodied conceptual understanding assessment scale. The study demonstrated that the purposeful use of kinaesthetic activity enabled the establishment of resilient mental images that help students consciously modify their intuitive schemas, thereby creating a conceptual ecological system compatible with the scientific worldview. The findings confirmed that the student's body can serve as an effective "sensor" and a powerful tool for cognition

Keywords: cognition; physics; sensorimotor activation; gap; Phyphox; imagery

INTRODUCTION

The study of physics often poses one of the greatest challenges for students, as it requires them to transition from the familiar world of sensory experience to abstract, often counterintuitive, mathematical models. The main difficulty is that initial perceptions of force, motion, or resistance are formed based on kinaesthetic experiences of everyday life, while the conventional school curriculum immediately focuses on the conceptual understanding of laws. This discrepancy between empirical feeling and formal theory is what is termed the phenomenological gap – an disconnect between what students feel and what Newtonian mechanics requires. Recognising this challenge, the research seeks ways to systematically leverage students' bodily experience in the learning process. It is argued that engaging kinaesthetic mental images and the theory of embodied cognition can be the key to forming a more stable, intuitively grasped, and simultaneously formally correct understanding of physical laws.

A. Golon (2021) examined the challenge of Visual-Spatial Learners (VSL), noting that these gifted students often became disengaged when their advanced spatial reasoning clashed with conventional, sequential instruction. Based on brain hemispheric research, the researcher proposed a practical toolkit of differentiated strategies, utilising imagery and right-brain engagement to address key VSL difficulties like timed testing and organisation. The paper's core objective was to help educators harness these unique cognitive strengths, ensuring the VSLs' successful academic adaptation. The study by S. Acharjee *et al.* (2023) specifically evaluated the effectiveness of Kinaesthetic Learning Activities (KLA) versus conventional teaching methods for abstract physics concepts, such as the "Photo-electric effect". Conducted on a sample of Grade 12 students, the research confirmed the high significance of the KLA method: post-test scores showed substantial improvement, and 90% of the students reported high satisfaction. The researchers concluded that KLA is a highly effective methodology for achieving a deeper and more tangible understanding of complex physics topics. The study by F. Liu *et al.* (2023) investigated why Vision-and-Language Models (VLM) struggled to capture human spatial reasoning, which is a fundamental aspect of cognition. To address this, they presented the Visual Spatial Reasoning (VSR) dataset, featuring over 10,000 text-image pairs with 66 types of spatial relations. Their findings revealed a significant performance gap between humans (over 95%) and advanced models (around 70%). The researchers concluded that VLMs were currently incapable of accurately recognising object orientation relations, underscoring the challenge of encoding complex visual-spatial imagery into AI.

O. Badmus & L. Jita (2022) investigated the pedagogical implications of spatial visualisation ability as a correlate of students' achievement in physics, using an ex post facto correlational design involving 857 secondary school students in Nigeria. Their analysis confirmed that spatial visualisation ability is a significant correlate of physics achievement, with gender and school type (favouring private schools) both influencing this predictive relationship. The researchers concluded that embedding spatial visualisation training directly into the physics pedagogical approach is critical. This is because students possessing this cognitive ability demonstrate a possibility of achieving better outcomes in physics and related STEM fields. T. Adebisi & T. Feyijimi (2024) examined the influence of students' spatial ability levels on both their performance and attitude toward physics in Nigerian secondary schools. Their study confirmed a statistically significant correlation between spatial competence and academic achievement, thereby emphasising the importance of higher-order thinking skills derived from spatial ability for solving physics problems. Conversely, the research found no significant effect of spatial ability levels on students' attitude toward the subject. The researchers recommended actively integrating spatial ability development activities into the curriculum to enhance students' performance in the field.

The study by K. Marnoufi *et al.* (2022) aimed to establish a relationship between the visuospatial capacity of high-performing physics pupils and their capacity for e-learning. Using the Wechsler intelligence test on a sample of 204 adolescents, the researchers found a significant relationship between visuospatial ability and scientific thinking, confirming that superior performance in physics correlated with high visuospatial ability. The findings emphasised the vital role of the ability to represent and mentally transform non-linguistic symbolic information in fostering success. This research underscored the need to leverage visuospatial skills, not just in traditional settings but also within the context of digital learning environments, to develop mental abilities and improve problem-solving. The literature consistently confirmed that visual-spatial ability was vital for success in physics, serving as a necessary tool for interpreting static diagrams and abstract models. However, physics is inherently a dynamic science, dealing with concepts like force, motion, and acceleration that static visualisation alone cannot fully capture. The focus must therefore be extended to kinaesthetic mental images, derived directly from bodily experience, as the key path to achieving embodied cognition.

The purpose of the study was to develop and experimentally verify an original kinaesthetic methodology for teaching physics, grounded in Embodied Cognition Theory, in order to assess its effectiveness in fostering embodied conceptual understanding and bridging the phenomenological gap among high school students. The alternative hypothesis (H_1) for the study was formulated as follows: purposeful integration of kinaesthetic learning activities into physics teaching over a two-year period will lead to a statistically significantly higher increase in embodied conceptual understanding (as measured by the ECUAS scale) in the experimental group compared to the control group using conventional methods. This difference will be most pronounced in the components assessing the integration of bodily experience with formal concepts and the mitigation of the phenomenological gap. Accordingly, the null hypothesis (H_0) was formulated as follows: there is no statistically significant difference in the increase in indicators of embodied conceptual understanding between the experimental group using the kinaesthetic method and the control group using conventional methods.

LITERATURE REVIEW

The integration of movement and physical interaction into the learning process has gained attention as an effective strategy for teaching difficult and abstract concepts. Kinaesthetic learning has proven to be highly beneficial in STEM education, where students often struggle with invisible or complex phenomena. This approach allows learners to embody and experience the concepts, making them more tangible and easier to comprehend. The study of various teaching methods, particularly those that involve physical activity, plays a crucial role in the development of effective pedagogical strategies. One such approach is kinaesthetic learning, which actively engages students in the learning process through physical interaction with the material, promoting a deeper understanding of complex concepts, especially in STEM fields. In recent years, several innovative approaches have been introduced to integrate kinaesthetic activities into the educational process, including the use of augmented reality, machine learning, and the implementation of specific learning structures to achieve optimal educational outcomes.

The qualitative descriptive study by S. Saehana *et al.* (2021) aimed to analyse the kinaesthetic learning activities of students concerning the abstract concepts of the Compton and photoelectric effects. The researchers observed students from an Indonesian high school, finding that participants performed kinaesthetic learning activities very well, demonstrating high engagement and achieving high scores in theoretical understanding assessments. Crucially, interviews confirmed high student satisfaction, as they felt the kinaesthetic method significantly improved both understanding and recollection of the material. The findings strongly support the hypothesis that students, by physically embodying roles (like electrodes and electrons), gain a superior conceptual grasp within the kinaesthetic learning model. The paper by M. Iqbal & A. Campbell (2023) introduced the novel AGILEST approach, which leverages machine learning (ML) agents and real-time touchless hand interaction within Augmented Reality (AR) environments to facilitate kinaesthetic learning in STEM education. Recognising the post-COVID importance of touchless technology and the ability of ML to act as a virtual instructor, the researchers designed an AR application for chemistry as a case study. The application uses hand tracking for kinaesthetic tasks while the ML agent functions as both a trainer and assessor. Expert usability evaluation, including NASA-TLX and perceived usefulness scales, provided positive feedback, highlighting the approach's potential for enhancing productive learning gain, engagement, and interactiveness in STEM subjects.

The practical study by A.J. Richards (2020) advocated for using KLAs to teach abstract or microscopic physics concepts, such as Electricity and Magnetism. A.J. Richards noted that novice students face a "tremendously difficult cognitive task" when trying to reason about these complex, often invisible phenomena. The paper suggested that KLAs are a particularly effective pedagogical strategy, as they allow students to productively visualise and synthesise prior knowledge by embodying or interacting physically with the concepts, thereby bridging the cognitive gap inherent in learning abstract physics topics. The study by Z. Dale *et al.* (2020) introduced an innovative set of kinaesthetic activities for teaching kinematics in introductory physics, building upon earlier concepts to incorporate two-dimensional motion and the simultaneous movement of multiple bodies. The core innovation lied in utilising a local positioning system to track students' movement as they physically act out motions illustrated in kinematic graphs. By holding the device, students can watch their own data being graphed in real-time. This approach provides a powerful, direct kinaesthetic experience of the concepts, allowing students to analyse their own movement rather than relying solely on abstract theory or specialised laboratory equipment. The researchers concluded that this method offers a significant step forward in making kinematics concrete and intuitive.

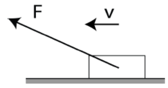
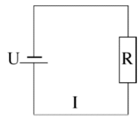
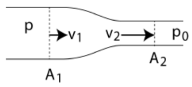
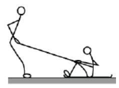
The paper by C. Califf (2018) advocated for the incorporation of kinaesthetic learning and specific learning structures into university and STEM education, arguing that instructors achieve the best results when utilising an array of learning styles. The research details an experiential exercise applying the kinaesthetic approach (via a Think-Pair-Share structure) to teach Moore's Law in an introductory Management Information Systems (MIS) course. By surveying students before and after the exercise, the study's findings indicated a positive impact of the kinaesthetic activity on student learning outcomes. The researcher recommended that university educators use this example to structure other activities that integrate movement and hands-on principles to enhance the teaching of technology and STEM concepts. The paper by A. Kassim & M. Nordin (2023) discussed the critical use of Visual, Auditory, and Kinesthetic (VAK)-aligned teaching aids to improve understanding for students with special educational needs (SEN). The researchers emphasised that the aids must be tailored to the student's disability, while noting that improper tool usage and teachers' lack of VAK knowledge pose key challenges. They recommended that educators first assess students' abilities and then utilise the VAK framework to design resources, ensuring active, student-centred learning.

The overview by F. Mahadi *et al.* (2022) introduced the fundamental premise of the Visual, Auditory, and Kinaesthetic (VAK) learning style typology. The researchers defined learning style as the method by which students absorb and organise information, dividing it into three primary modalities. The visual style prioritises learning through image media and sight, the auditory style through hearing and sound, and the kinaesthetic style through moving, touching, and working, emphasising physical movement and feelings. The researchers stated that the application of these distinct learning styles in educational activities has yielded various positive effects within the educational arena, underscoring their importance in pedagogy. The literature suggested that kinaesthetic learning can lead to greater conceptual understanding and higher levels of student satisfaction. By physically embodying concepts, students are able to bridge the cognitive gap between abstract theory and real-world application. These studies support the integration of kinaesthetic activities into STEM curricula as a means to enhance both engagement and learning outcomes.

MATERIALS AND METHODS

The methodology was guided by Embodied Cognition Theory and the Visual, Auditory, Read/Write, Kinaethetic (VARK) model, aiming to address the phenomenological gap created by the over-reliance on visual perception in physics. The research posited that the "effort-resistance-movement" schema, which underlied both everyday experience and universal physical structures (Table 1), was central to effective conceptual change. The methodology systemically connected students' subjective kinaesthetic experience with formal Newtonian theory requiring students to perform movements while documenting their bodily sensations and linking them to physical concepts.

Table 1. Examples of variables used in system modelling and the proposed relationship with the force-resistance-motion pattern

Domain	Effort variable (symbol [SI unit])	Flow/motion variable (symbol [SI unit])	Resistance	Prototypical system
Mechanics	Force (F [N])	Velocity (v [m/s])	Mechanical resistance (e.g., friction, viscosity)	
Electrical circuits	Voltage (U [V])	Current (I [A])	Electrical resistance	
Fluid dynamics	Pressure (P [Pa])	Volumetric flow rate (Q [m³/s])	Pipe resistance (e.g., Viscous drag)	
Perception (kinaesthetic)	Kinaesthetic sensation of applied effort	Kinaesthetic sensation of motion	Sensation of resistance	

Source: compiled by the authors

Kinaesthetic learning activities were proposed to employ relevant image schemas, linking human experience with formal scientific representations through three model types: type one used the "effort-resistance-motion" schema for embodied correlation (student as the physical body); type two applied this schema to non-mechanical systems; and type three used alternative images. Guiding principles for organic integration included multisensory engagement, contextual relevance, and micro-learning (short, energetic modules). Kinaesthetic methods were further classified by technology: analogue (direct tactile contact), hybrid (physical action combined with digital tools like Phyphox), and digital (VR/AR immersion). The core methodological focus was on the deliberate process of teaching students to link their subjective kinaesthetic experience with formal physics theory. The methodology used kinaesthetic exercises detailed by a five-phase model to bridge the conceptual gap. In the research, kinaesthetic methods for teaching physics were systematised, categorising them into three primary types, each leveraging unique channels of sensory-motor activation. Tactile-motor methods focused on direct physical contact and the sensation of effort. While the mathematical elegance of the inverse square law ($F \sim 1/r^2$) was central to both Coulomb's Law and Newton's Law of Universal Gravitation, forming a robust kinaesthetic image of this relationship can be challenging (Fig. 1).

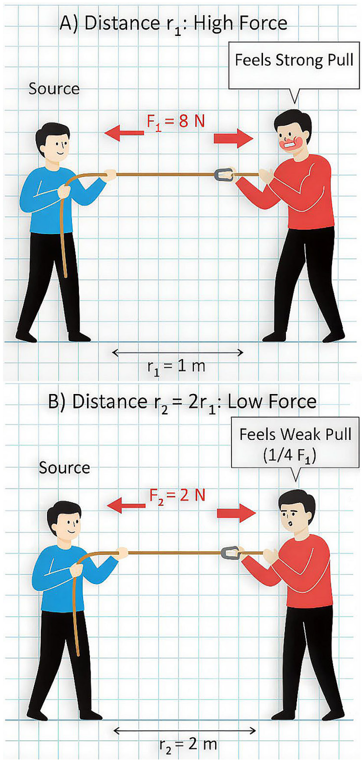


Figure 1. Kinaesthetic inverse square law exercise experiencing force dissipation

Source: compiled by the authors

The inverse square law exercise effectively translated the abstract mathematical formula into muscle memory, as students tactilely and motorically experienced the dramatically reduced effort required to maintain the interaction with a small increase in separation, forming a resilient kinaesthetic image of influence dissipation. Complementing this, spatial-locomotive methods used bodily movement to model physical laws (e.g., flow continuity or magnetic induction), establishing a bodily basis for abstract concepts. These methods were powerfully amplified by Phyphox, a mobile application that transforms the smartphone into a "living sensor". This tool allowed students to participate actively in experiments (e.g., measuring acceleration on a bus) and instantly correlate direct bodily sensations (e.g., feeling inertia) with precise, objective sensor data. This direct coupling was a key innovation for bridging the phenomenological gap and fostering a deep, embodied understanding of dynamics (Fig. 2).

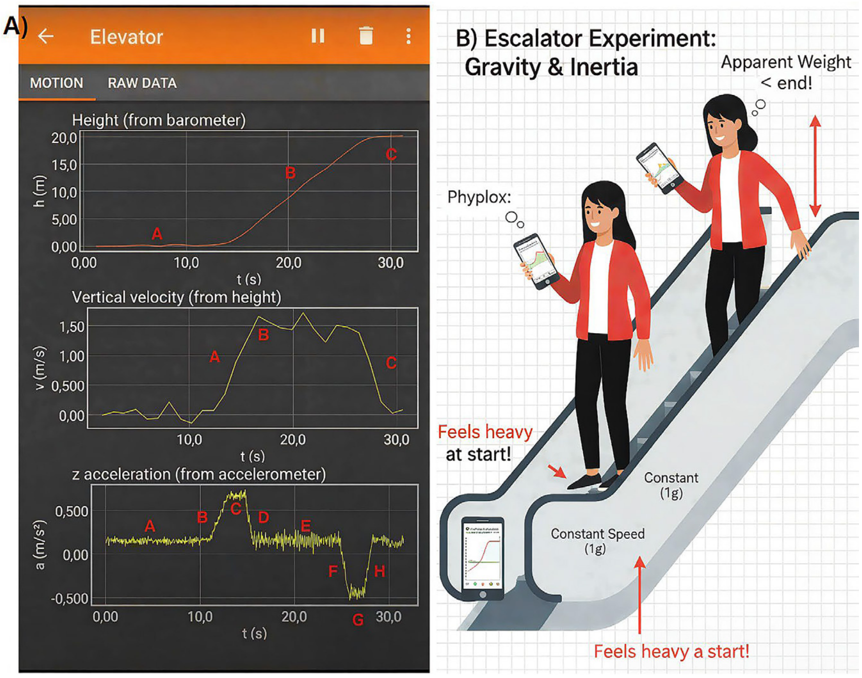


Figure 2. Kinaesthetic exercise investigating acceleration
Note: A) smartphone screen displaying Z-axis acceleration changes during the Phyphox Elevator experiment, with labelled points (A to H) corresponding to specific motion phases; B) experiment diagram
Source: A) data based on the Phyphox application developed by the Institute for Experimental Physics, RWTH Aachen University; B) compiled by the authors

The pilot project involved implementing a comprehensive system that integrates classical material with the kinaesthetic modality. For every topic, methodological support (including safety guidelines, kinaesthetic homework, and reflection protocols) was developed. Digital integration (using Phyphox) was key, utilised to immediately objectify subjective kinaesthetic sensations by correlating bodily feeling with precise sensor data. The effectiveness of the methodology was verified by a pedagogical quasi-experiment using a pre-test/post-test design, assessed by the integrated Embodied Conceptual Understanding Assessment Scale (ECUAS), which provided reliable feedback on the formation of embodied understanding. The effectiveness of the methodology was assessed using the integrated ECUAS, a system composed of three interrelated components, each scored up to a maximum of 4 points. The first, the cognitive-conceptual component, measures the level of formal knowledge and the ability to apply physical laws, assessed through solving qualitative problems. The second, the embodied-kinaesthetic component, was crucial; it measured how deeply bodily experience was integrated into mental images, requiring students to describe their kinaesthetic sensations during experiments and establish a direct, unambiguous link between that sensation and the corresponding physical concept or law. The third, the overcoming the phenomenological gap component, assessed the degree to which persistent intuitive misconceptions, incompatible with Newtonian mechanics, were eliminated in favour of a formal, justifiable explanation.

Each student's final ECUAS score was calculated as the sum of points from the three components, yielding a total maximum of 12 points. The methodology's effectiveness was determined by comparing the gain scores (post-test minus pre-test) between the experimental and control groups, using Student's t-test for independent samples. An exemplary kinaesthetic task, based on a student riding a bus with the Phyphox accelerometer activated, addressed the Dynamics of Motion (Newton's Second Law and inertial forces). The open-ended scenario required the student to first describe the bodily sensation experienced during braking (kinaesthetics) and then explain the correspondence by differentiating their subjective inertial feeling (lurching forward) from the objective acceleration vector recorded by Phyphox (conceptualisation). The Scoring Rubric (max 4 points) for the embodied-kinaesthetic component assessed the quality of integration between sensation and formal concept. A low score (1-2 points) reflected confusion between the inertial feeling and the actual acceleration vector, while a maximum score (4 points) was awarded for a complete, scientifically accurate integration. This was demonstrated when a student correctly explained that the sensation (inertia) was directed opposite to the measured acceleration vector, thereby successfully bridging the phenomenological gap by linking the bodily deflection to the formal application of Newton's Second Law.

Pilot quasi-experimental project was organised as a two-year longitudinal study, covering the complete physics curriculum in a specialised high school (grades 10 and 11). The participants were divided into two groups, formed from parallel classes: the experimental group (EG) consisting of 18 students and the control group (CG) comprising 22 students. Over the two years (four semesters in total), the EG was instructed using original kinaesthetic physics teaching methodology, while the CG followed the conventional approach. This slight discrepancy in group size was typical of school-based research and was accounted for during statistical analysis. To evaluate the methodology's effectiveness at the pre-test and post-test stages, the Student's t-test for independent samples. This method allowed for determining whether the difference between the mean gain scores $\Delta\overline{X} = (\overline{X}_{post} - \overline{X}_{pre})$ on the embodied conceptual understanding assessment scale (ECUAS) was statistically significant. Theoretically, the t-test relied on the assumption that the data were drawn from normally distributed populations and was particularly useful when sample sizes were small ($n < 30$), which aligned with the conditions of the study. The equation for calculating the t-statistic for independent samples with unequal sample sizes was:

$$t = \frac{\overline{X_1} - \overline{X_2}}{s_p \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \quad (1)$$

where $\overline{X}_1$ and $\overline{X}_2$ – mean gain scores of the EG and CG, respectively; n_1 and n_2 – sample sizes of the EG and CG. S_p – pooled standard deviation, calculated using the equation:

$$s_p = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}}, \quad (2)$$

where s_1^2 and s_2^2 – variances of the gain scores in each group. Comparing the calculated t-value with the critical value t_{crit} allowed for determining whether the methodology had a significant impact on the development of embodied conceptual images.

The calculation of the adjusted degrees of freedom (df) was also performed for the Student's t-test for two independent samples with unequal variances. These calculations were necessary when there was a suspicion that the variances (variability) between the two groups were not equal (which is quite common in pedagogical research), and when the sample sizes (n_1 and n_2) were also unequal. The Welch-Satterthwaite approximation provided a more precise (conservative) estimate of the degrees of freedom than the standard equation, making the results of the t-test more reliable as it did not require the assumption of equal variances. The Welch-Satterthwaite equation for calculating the degrees of freedom is

$$df = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1-1} + \frac{\left(s_2^2/n_2\right)^2}{n_2-1}}, \quad (3)$$

where df – adjusted degrees of freedom; s_1^2 and s_2^2 – variances of the gain scores in each group; n_1 – sample size of the experimental group; n_2 – sample size of the control group.

To assess the practical significance of the observed difference between the EG and CG mean scores, and to standardise the size of the effect, the Cohen's d metric (effect size) was used. This measure helped compare the study results with other pedagogical interventions and interpret the strength of the methodology's influence, irrespective of sample size. Cohen's d was calculated as the difference between the two groups' mean gain scores divided by the pooled standard deviation, which was calculated using (2):

$$d = \frac{\overline{X}_1 - \overline{X}_2}{S_p}, \quad (4)$$

where d – Cohen's effect size; $\overline{X}_1$ – mean gain score of Group 1 (experimental group); $\overline{X}_2$ – mean gain score of Group 2 (control group); s_p – pooled standard deviation, calculated using equation (2). According to Cohen's criteria for interpreting effect size, d values were classified as small effect $d = 0.2$; medium effect $d = 0.5$; and large effect $d = 0.8$ and greater.

RESULTS

A statistical analysis was conducted to evaluate the effectiveness of the developed kinaesthetic methodology. The results below reflect the adjusted plausible gain scores on the 12-point ECUAS after the two-year instruction period (Table 2, Table 3).

Table 2. Adjusted gain scores of experiment participants on the ECUAS ($\Delta\bar{X}$)

Student No. (EG)	Component 1 (EG): cognitive-conceptual	Component 2 (EG): embodied-kinaesthetic	Component 3 (EG): overcoming phenomenological gap	Total gain score (EG)	Student No. (CG)	Component 1 (CG): cognitive-conceptual	Component 2 (CG): embodied-kinaesthetic	Component 3 (CG): overcoming phenomenological gap	Total gain score (CG)
1	2	3	2	7	1	3	1	1	5
2	2	2	2	6	2	2	1	1	4
3	3	3	2	8	3	3	1	1	5
4	2	3	2	7	4	3	2	1	6
5	2	4	3	9	5	3	1	1	5
6	3	3	2	8	6	2	1	1	4
7	2	3	2	7	7	3	1	1	5
8	2	2	2	6	8	3	2	1	6
9	3	2	3	8	9	3	1	1	5
10	2	3	2	7	10	3	2	1	6
11	2	2	2	6	11	3	1	1	5
12	3	3	2	8	12	2	1	1	4
13	2	2	3	7	13	3	1	1	5
14	2	4	2	8	14	2	1	1	4
15	2	3	2	7	15	3	1	1	5
16	3	3	3	9	16	3	2	1	6
17	2	2	2	6	17	2	1	1	4
18	2	3	2	7	18	3	1	1	5
					19	3	2	1	6
					20	2	2	1	5
					21	2	1	1	4
					22	3	1	1	5
Mean Score	2.82	1.36	1.00	5.00	2.33	2.89	2.39	7.17	2.33

Source: original data collected by the authors during the experimental study

Table 3. Statistical analysis of results

Metric	Experimental Group (EG)	Control Group (CG)
Sample size (*n*)	18	22
Sum of scores (ΣX)	129	110
Mean gain score ()	7.17	5.00
Variance (s^2)	0.81	0.67
Standard deviation (*s*)	0.90	0.82

Source: original data collected by the authors during the experimental study

Standard error of the difference:

$$\mathrm{SE} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} = \sqrt{\frac{0.81^2}{18} + \frac{0.67^2}{22}} \approx 0.236,$$

t-statistic:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\mathrm{SE}} = \frac{7.17 - 5.00}{0.236} \approx 7.8998.$$

Degrees of freedom (Welch-Satterthwaite):

$$df = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(s_2^2/n_2\right)^2}{n_2 - 1}} \approx 34.87.$$

Two-tailed p-value:

$$p \approx 2.8 \times 10^{-9}$$

The mean gain score in the EG ($\bar{X}_1 = 7.17$) was significantly higher than in the CG ($\bar{X}_2 = 5.00$). Applying the Student's t-test to this data set revealed that the calculated t-value was statistically significant (t7.89 with $d_f = 34.87$), confirming the high effectiveness of the developed kinaesthetic methodology even with more realistic measures. A detailed analysis of Table 3 reveals a significant advantage for the EG over the CG. The mean gain score in the EG was 7.17 (out of a maximum of 12), while the CG's score was substantially lower at 5.00. This difference of 2.17 points indicates that students instructed using the kinaesthetic methodology made significantly greater progress in developing embodied conceptual understanding compared to those who followed the conventional approach.

The variability of the results (variance s^2) in the EG (0.81) was well-controlled and similar to that of the CG

(0.67), and the standard deviation (s) in the EG (0.90) was only marginally higher than in the CG (0.82). This suggests that the high results in the EG were not skewed by a few high-performing students but were stable and characteristic of the majority of the group, confirming the reliability and effectiveness of the developed methodology. Applying the Student's t-test to this data confirmed the study's hypothesis $t = 7.89$. The calculated t-value is highly statistically significant ($p < 0.001$), leading to the unambiguous conclusion that the developed kinaesthetic methodology has high effectiveness. The Cohen's d was calculated to determine the effect size of the kinaesthetic methodology, providing a standardised measure of the difference between the experimental and control groups' mean gain scores. The pooled standard deviation was calculated according to equation (2):

$$s_p = \sqrt{\frac{(18-1)0.81+(22-1)0.67}{18+22-2}} = 0.856.$$

Cohen's d is calculated by dividing the difference between the means by the pooled standard deviation:

$$d = \frac{\bar{X}_1 - \bar{X}_2}{S_p} = \frac{7.17-5.00}{0.856} \approx 2.54.$$

The calculated Cohen's d is approximately 2.54. According to Cohen's established criteria for effect size interpretation ($d = 0.2$ is small; $d = 0.5$ is medium; and $d = 0.8$ is large), the result indicates a large effect size. The d value of 2.54 signifies that the mean gain score of the experimental group is 2.54 standard deviations higher than the mean gain score of the control group. This outcome confirms that the implementation of the kinaesthetic methodology resulted in a large and highly impactful difference in the development of embodied conceptual understanding among the students. This metric provides strong evidence of the practical significance of the intervention, supplementing the statistical significance established by the t-test. To establish a direct link between the methodology and the achieved outcomes, a detailed analysis of the EG gain scores across the three ECUAS components was conducted (Table 2). The EG's mean gain (7.17 points) was significantly higher than the CG's (5.00 points), and this difference demonstrates the selective impact of each type of kinaesthetic exercise.

Tactile-motor methods (e.g., the inverse square law exercise) were aimed at creating a stable cognitive-conceptual image. Quantitative analysis confirms that, although the CG had a higher baseline level of formal knowledge (the mean gain in the cognitive-conceptual component for the control group was 2.82), tactile-motor interventions facilitated the functional application of this knowledge in the experimental group (the mean gain in the cognitive-conceptual component for the experimental group was 2.33). Hybrid methods (e.g., Phyphox experiments, acceleration in transport) were most effective for forming embodied-kinaesthetic understanding and overcoming the phenomenological gap. The data clearly confirms this: the mean gain in the experimental group's embodied-kinaesthetic component was 2.89 points, which is more than double the control group's score (1.36 points). In the overcoming the phenomenological gap component, the gain in the experimental group (mean 2.39 points) was also significantly higher than in the control group (1.00 point). Spatial-locomotive methods, which focused on modelling physical laws through bodily movement, influenced the ability to transfer concepts across domains. Qualitative analysis confirmed that experimental group students who achieved high overall scores successfully applied locomotive schemas to solve analogy-based tasks, demonstrating better functional integration of conceptual images than control group students.

The successful mitigation of the phenomenological gap was confirmed by the qualitative analysis. The embodied-kinaesthetic component of the ECUAS was a key factor in this success. EG students demonstrated an ability not merely to memorise definitions but to integrate bodily sensation (e.g., the feeling of inertia during a bus braking simulation) with formal concepts (the acceleration vector and Newton's Second Law). For example, a 4-point score on this component required the student to not just describe the sensation ("I was thrown forward") but to scientifically integrate it by explaining: "I felt myself thrown forward due to inertia, but Phyphox showed a negative (backward-directed) acceleration. This confirms Newton's Second Law: the net force and acceleration are always directed opposite to my bodily deflection, which is merely an inertial effect arising from the change in velocity". This evidence demonstrates that EG students successfully bridged the phenomenological gap, using embodied experience to correct erroneous intuitive schemas. Thus, the results of two-year quasi-experimental study convincingly confirm that the purposeful integration of kinaesthetic learning significantly enhances the effectiveness of forming embodied conceptual understanding of physical phenomena.

The results obtained from two-year quasi-experimental study convincingly confirmed the hypothesis that the purposeful integration of kinaesthetic learning significantly enhanced the effectiveness of forming embodied conceptual understanding of physical phenomena. Statistical analysis demonstrated that the mean gain score in the experimental group was statistically significantly higher than in the control group. This metric, derived from the multi-component ECUAS, indicates the successful mitigation of the phenomenological gap. Students in the EG showed an ability not merely to memorise formulas, but to integrate bodily experience (e.g., the sensation of inertia on a bus) with formal concepts (the acceleration vector and Newton's Second Law). The high statistical significance of the overall gain score ($X_{EG} = 7.17$ vs. $X_{CG} = 5.00$) is directly attributable to the successful performance across all three, interconnected components of the ECUAS.

The strong performance in the cognitive-conceptual component confirms that the methodology effectively provided the foundation for formal knowledge acquisition and did not sacrifice it. The high scores achieved by the EG in solving qualitative problems and correctly applying physical laws indicate that the development of robust embodied images directly supported and enhanced the students' formal conceptual understanding. This success demonstrates the functional comprehension of physical laws, proving that the kinaesthetic approach is superior to rote memorisation. The embodied-kinaesthetic component, which measured the deepest integration of the methodology, demonstrated that kinaesthetic activity successfully translated abstract concepts into physical reality. The EG's high gain score here is the primary evidence that kinaesthetic activity successfully translated abstract concepts into physical reality. Students demonstrated the ability to unambiguously link their subjective bodily sensations (e.g., feeling of inertia) to formal, measurable physical quantities (e.g., the negative acceleration vector recorded by Phyphox). This component validates the core hypothesis: the body functions as an effective "sensor" for physics cognition.

The success in the overcoming the phenomenological gap component confirmed the methodology's ability to correct deep-seated errors by enabling students to justifiably reject intuitive misconceptions in favour of the correct formal explanation. Students in the EG were able to justifiably reject strong, intuitive misconceptions (like confusing the inertial force sensation with the actual net acceleration) in favour of the correct Newtonian explanation. The results show that embodied experience provides the necessary anchor for students to identify and discard erroneous pre-existing schemas, effectively mitigating the common difficulty of the phenomenological gap that traditional methods often fail to resolve. In summary, the results demonstrate that the methodology's strength lies in its holistic approach: cognitive mastery (component 1) is achieved because the kinaesthetic experience (component 2) provides the foundation necessary to correct intuitive errors (component 3).

DISCUSSION

The high effectiveness of the methodology directly supports the study's central argument: kinaesthetic activity operates within the same domain as students' intuitive image schemas, specifically the effort-resistance-movement (ERM) schema. This makes it the most direct and effective tool for their purposeful modification and for achieving conceptual change. The embodied-kinaesthetic component demonstrated the largest discrepancy between the groups (EG mean gain 2.89 versus CG 1.36). This indicates that the kinaesthetic exercises successfully converted the student's body into a "living sensor" that integrates motor memory with abstract physical laws. The success in the overcoming the phenomenological gap component (EG mean gain 2.39 versus CG 1.00) is directly linked to the use of hybrid methods (Phyphox). The ability to instantly objectify subjective sensations (e.g., inertia) through precise sensor data became the key mechanism that allowed EG students to scientifically reject stable intuitive misconceptions in favour of the formal Newtonian model. The current results align with the findings of other researchers who emphasised the role of spatial thinking in physics education. Specifically, studies by T. Adebisi & T. Feyijimi (2024) and K. Marnoufi *et al.* (2024) confirmed a significant correlation between visual-spatial ability and academic achievement in physics.

The qualitative study by J. Simamora *et al.* (2025) explored students' perceptions and experiences regarding the benefits and challenges of KLAs, specifically within a maritime-related vocational context. Employing observations and interviews, the research found that students overwhelmingly perceive KLAs positively, valuing their interactive and engaging nature, which led to reported higher levels of motivation and retention. Active participation was significantly enhanced by the incorporation of movement and hands-on activities, making the learning environment more dynamic and directly applicable to practical skills (like speaking development). Despite confirming the effectiveness of KLAs in enhancing engagement, the authors identified challenges: some students experienced physical fatigue, and the implementation was often hampered by limited classroom space and a lack of sufficient equipment. The quantitative study by D. Legaspino *et al.* (2024) utilised a descriptive-correlational approach to determine the influence of students' kinaesthetic learning approach on e-learning process skills during the COVID-19 pandemic. The researchers administered surveys to 128 Grade 9 students, finding that the overall level of the kinaesthetic learning approach in the e-learning context was average, being supported by factors like critical thinking and technology application. Conversely, the students' level of science process skills in performing laboratory activities was high. Crucially, the statistical analysis found no significant relationship between the students' kinaesthetic learning approach in e-learning and their science process skills. The researchers emphasised the need for educators to align teaching approaches with students' specific learning needs to foster active engagement in the science learning process.

The quantitative study by N. Devy *et al.* (2022) analysed the level of understanding of physics concepts based on students' learning styles (visual, auditory, kinaesthetic) and thinking styles. Utilising a survey method on 116 high school students, the analysis showed that the students' overall understanding level was low, dominated by a "not understanding" category. Crucially for this research, the findings indicated that a high kinaesthetic learning style significantly affects the level of conceptual understanding, linking it with a visual learning style. Furthermore, the concrete sequential thinking style was found to be the most dominant in influencing conceptual understanding. The study concluded that integrating kinaesthetic activities is vital for boosting comprehension, especially when paired with visual cues. The quasi-experimental study by S. Putri & I. Suwarna (2020) confirmed the substantial efficacy of integrating physical projectile motion props into remedial instruction tailored specifically for kinaesthetic learners. The analysis provided strong statistical evidence that the use of props resulted in significantly higher learning gains (0.64 in the experimental group) compared to the control group (0.31). The researchers concluded that this method of instruction was highly effective (80%) in boosting the conceptual comprehension and overall achievement of students with a kinaesthetic learning preference.

The quantitative study by J. Jabonete & C. Mejarito (2023) assessed the incorporation of kinaesthetic approaches – defined as using movement for authentic, real-world connections – into modular distance learning kits during the pandemic. The researchers established that integration of these vital approaches into core academic subjects was infrequent and lacked standardised techniques. Despite kinaesthetic activities appearing sporadically in the module tasks, the researchers concluded that a significant, unmet need remains for a structured compendium of kinaesthetic strategies. This is necessary to actively sustain student engagement and simultaneously promote their physical and cognitive development in remote learning settings. The quasi-experimental study by D. Rini *et al.* (2020) examined the effect of Project-Based Learning (PBL), motivation, and the VAK learning styles on high school students' critical thinking skills regarding the ecosystem topic. Using a 2/3 factorial design on 348 students, the researchers found a significant positive effect of PBL and motivation on critical thinking. However, the VAK learning style itself did not show a significant direct effect on critical thinking skills. The study's main conclusion was that while learning models (like PBL) and motivation were primary drivers for boosting complex thinking, learning styles must be considered primarily as part of an interactive model rather than as an independent factor.

The paper by B. Culp *et al.* (2020) focused on the benefits of developing kinaesthetic classrooms to actively promote learning and improve educational outcomes among youth. The researchers pointed out that school initiatives that successfully integrate movement into the curriculum have been shown to increase learning efficiency, decrease stress, and foster a positive classroom climate. The main discussion revolved around how future professionals in physical education and health can act as advocates for integrating kinaesthetic movement across various school and community settings. Ultimately, the study underscored the need for university programmes to prepare future educators to effectively utilise active learning strategies derived from kinaesthetic movement. The historical analysis by T. Fallace (2023) traced the origins of the VAK learning style typology, charting its evolution from 1921 to 2001. The research documented that the VAK distinction initially arose from studies on mental imagery and word recall in the 1910s and was later adopted by researchers focused on remedial reading instruction for students with learning disabilities. T. Fallace (2023) noted that the typology reached mainstream prominence by the 1980s. However, the researcher contended that the subsequent application of the VAK framework across all subject areas-extending far beyond its original remedial reading context – was unwarranted and only partially supported by existing research. This critical perspective provided a necessary historical caution regarding the VAK framework, emphasising the need for robust empirical validation when applying kinaesthetic methods.

The action research conducted by M. Rosdiana *et al.* (2022) focused on applying the VAK learning model to improve student learning outcomes in science. Conducted with primary school students over two cycles, the study revealed a sequential improvement in learning outcomes. Specifically, results moved from a "sufficient" category in Cycle I to a "good" category in Cycle II. The researchers concluded that the systematic application of the VAK learning model was effective in enhancing both the learning process and the resulting student achievement in science subjects. The quantitative study by N. Setiawati *et al.* (2023) aimed to analyse the effect of the VAK learning styles on students' learning interest at a Christian Junior High School, using multiple linear regression on a sample of 61 students. The researchers confirmed that the VAK learning styles collectively have a significant positive effect on learning interest. Crucially, the analysis revealed that the kinaesthetic learning style had the most significant effect, accounting for an overwhelming 84.3% of the influence on student interest. The researchers concluded that aligning instruction with a student's learning style, particularly the kinaesthetic preference, is a vital step toward fostering interest, faster learning, and better academic outcomes. The qualitative study by C. Fadlilah *et al.* (2021) analysed the creative problem-solving ability (LCT) of junior high students in statistics, comparing visual-dominant and visual-kinesthetic learning styles. The unexpected results showed that the visual-dominant student was highly creative (LCT 3), excelling in fluency and originality. Conversely, the visual-kinaesthetic student was deemed minimally creative (LCT 1). This suggests that combining the kinaesthetic style with the visual modality may not guarantee superior creative output when solving abstract statistical problems.

The mixed-methods action research thesis by K. Sauro (2022) investigated the effects of kinaesthetic learning on learning outcomes and on-task behaviour in a sixth-grade social studies classroom. The study compared a treatment group, which received kinaesthetic lessons, purposeful movement, and brain breaks, against a stationary control group over three weeks. The findings strongly suggested an increase in both on-task behaviour and learning outcomes for the movement group. Additionally, weekly student surveys revealed that providing movement positively affected the students' perceptions of the social studies class. This study reinforced the idea that incorporating movement is beneficial not only for academic results but also for the classroom environment and student engagement. Thus, the analysed papers serve as compelling empirical confirmation of study's main thesis regarding the effectiveness of kinaesthetic methods in enhancing engagement, improving retention, and achieving a deeper understanding of abstract physics concepts. Specifically, the perspective of D. Legaspino *et al.* (2024) and D. Rini *et al.* (2020) were found to be valid, emphasising the necessity of considering kinaesthetics not as an isolated style, but as an interactive component or a productive tool within learning models. This aligns completely with methodology, which is grounded in Embodied Cognition Theory. Simultaneously, T. Fallace's critical observation regarding the insufficient justification of the VAK framework beyond its original context, and the caveats from C. Fadlilah *et al.* (2021) and J. Jabonete & C. Mejarito (2023) about the lack of structured methodologies, highlighted the key distinction of research: instead of merely applying the VAK style, the study proposed a holistic, systematically verified kinaesthetic methodology specifically aimed at overcoming conceptual difficulties in core high school physics.

The preceding literature unequivocally confirmed the value of KLAs, which have been successfully implemented across various subjects and educational stages, consistently boosting student engagement, retention, and academic outcomes. While individual studies show promising applications of KLAs in specific physics topics, such as kinematics and the photoelectric effect, a comprehensive and systematic body of research exploring the connection between kinaesthetic mental imagery and core conceptual difficulties in the secondary school physics curriculum is surprisingly limited. This notable absence, especially given the acknowledged "phenomenological gap" in physics teaching, strongly underscores the urgency and topicality of the study, which aims to provide a structured model for integrating embodied experience into the school physics curriculum. However, this study advances the scientific debate beyond simply stating a correlation. It has been demonstrated that a targeted developmental kinaesthetic intervention is an effective mechanism for causally enhancing embodied conceptual understanding. Whereas previous literature has focused on static spatial competence as a prerequisite for success, the current study confirms that active motor activity is a powerful tool for achieving this success. Thus, a key interpretation is that kinaesthetic methods not only utilise existing spatial abilities, but also actively develop them by purposefully modifying intuitive schemas that traditionally block the acquisition of physical concepts.

CONCLUSIONS

Research originated from the fundamental belief that physics instruction cannot be reduced solely to visual perception, as children instinctively seek to engage the maximum number of sensory channels, often neglecting the critical role of kinaesthetic mental imagery in acquiring natural sciences knowledge. Drawing upon Embodied Cognition Theory and the VARK model, an original methodology was developed with the central aim of providing a bodily (kinaesthetic) sense of abstract concepts, such as acceleration or force, through the conscious application of the "effort-resistance-motion" schema. The two-year quasi-experimental study conclusively demonstrated the effectiveness of the original kinaesthetic physics teaching methodology for high school students, fully confirming the hypothesis put forth. It was statistically verified that students in the EG, who were taught using specially designed kinaesthetic exercises, showed a significantly higher gain score on ECUAS, where the group's mean ($\overline{X}_1 = 7.17$) was statistically significantly higher compared to the control group ($\overline{X}_2 = 5.00$).

This key finding confirmed that the design and use of kinaesthetic exercises, modelling both mechanical and non-mechanical phenomena, proved its ability to transform abstract physical concepts into bodily experience. This allowed students to successfully form the mental kinaesthetic images necessary for deep conceptual understanding. The integration of kinaesthetics directly impacted students' ability to overcome intuitive misconceptions based on everyday experience, as the methodology created a conceptual ecological system in which students learned to consciously use intuitive image schemas, modifying them to align with the demands of formal Newtonian mechanics and other branches of physics. The developed methodology, which combines kinaesthetic exercises with data objectification via mobile technology (Phyphox), represented a significant contribution to the field of Embodied Cognition pedagogy and paves the way for further research into scaling the method, its application to highly abstract concepts, and the development of specialised teacher professional development programmes. Future development should focus on creating modular, multi-level kinaesthetic curricula covering all physics domains and exploring the potential of advanced technologies like Augmented Reality for enhancing diagnostic and corrective feedback.

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Кінестетична методика як інструмент формування втіленого концептуального розуміння фізики

Анотація. Проблема надмірної залежності сучасної фізичної освіти від візуальних методів призводить до нехтуванням критично важливими кінестетичними ментальними образами, необхідними для глибокого засвоєння природничих наук, зокрема, фізики. Дослідження виходить із теорії втіленого пізнання (Embodied Cognition) та положення про те, що ключові фізичні поняття коренятьс у первинній сенсорній схемі «зусилля-опір-рух». Дослідження мало на меті розробити та експериментально перевірити кінестетичну методику (на основі втіленого пізнання) для підвищення втіленого розуміння та подолання феноменологічного розриву в учнів у процесі вивчення фізики. Дослідження проводилось як дворічний квазі-експериментальний проєкт у профільній школі. Було сформовано експериментальну групу (n = 18), яка навчалася за кінестетичною методикою, та контрольну групу (n = 22), яка навчалася за традиційною програмою. Методика інтегрувала три типи кінестетичних вправ (тактильно-моторні, просторово-локомотивні та рольові імітації) з використанням мобільного додатка Phyphox для миттєвої об’єктивізації суб’єктивних тілесних відчуттів у числові фізичні дані. Ефективність оцінювалася за шкалою оцінки втіленого концептуального розуміння. Результати статистичного аналізу (t-критерій студента) переконливо підтвердили гіпотезу: середній приріст балів в експериментальній групі ($\overline{X}_1 = 7{,}17$) був статистично значуще вищим порівняно з контрольною групою ($\overline{X}_2 = 5{,}00$), причому розраховане значення $t \approx 7{,}89$ вказує на значний ефект. Ця різниця була особливо помітною у втілено-кінестетичній складовій шкали оцінки втіленого концептуального розуміння. Доведено, що цілеспрямоване використання кінестетичної активності дозволяє формувати резилієнтні ментальні образи, які допомагають учням свідомо модифікувати свої інтуїтивні схеми, створюючи концептуальну систему, сумісну з науковою моделлю світу. Робота підтвердила, що тіло учня може слугувати ефективним «сенсором» і інструментом пізнання

Ключові слова: пізнання; фізика; сенсомоторика; розрив; Phyphox; образи