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Improving critical thinking through the cognitive loading control of working memory in introductory physics classes

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Improving critical thinking through the cognitive loading control of working memory in introductory physics class

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Abstract

The critical thinking process in physics problem solving has been observed to relate to working memory cognitive loading for engineering and technology students. A maximum working memory loading for a student can be assessed with a design that compartmentalizes the long term memory, short term information storage memory, and short term working memory for the manipulation of information. Innovative learning examples such as kinematics with algebraic complex numbers, relative velocity matrix transformation from 1-Dim to 2-Dim with created collision parameters, and collision with apparent mass from spring energy were delivered to students while the working memory cognitive loadings were controlled. Our assessment showed that a critical thinking element is only recognizable after a student could reach the working memory capacity required in the solving of a physics problem, and that long term memory capacity for various problems could serve as indicators for engineering sub-field selections in career advisement.

Keywords

Working memory, kinematics complex number, numerical matrix operation, relative velocity created parameter, collision apparent mass

Introduction

The transition from high school to college has been discussed by UCL in terms of the learning to become an independent thinker and to take responsibility for one's own study with critical and analytical thinking[1-2]. The simple concept of understanding after reading is augmented with four more concepts. The additional concepts are picking it apart, questioning it, evaluating it, and assessing it[3]. A 2013 description of "What is critical thinking" in terms of reflective thinking based on logic, rationality and synthesis was discussed with a conclusion that critical thinking must be hands-on while the theory of critical thinking can be taught[4]. In a 2015 Newsweek article addressing the high school education, the necessities of "rote memorization, deadening repetition and humility before intellects greater than your own" were emphasized for the critical thinking mandate because "one cannot think critically without quite a bit of knowledge"[5]. Memory traditionally has been classified into long term memory, short term information storage memory, and short term working memory for the manipulation of information, together with implicit memory for performing a procedural task[6]. Brain studies have pinpointed the role of dorsolateral prefrontal to working memory in terms of gene expression as well as improvement with transcranial simulation[7-9]. In helping student to learn physics, a maximum working memory loading for a student can be assessed with a design which delineates the above memory categories such that an instructor would know how to control the cognitive loading of working memory in the delivery of critical thinking with hands-on learning.

Critical Thinking Process

The question "What is critical thinking" can be understood in two different domains. The identification of the most significant factor (or principal factor) among several others after all the factors were identified using analytical reasoning is an important cognitive process. Lab examples include the diameter measurement uncertainty be identified as the significant factor in volume calculation uncertainty, since measurement uncertainty percentage would be counted twice when compared to length uncertainty percentage using calculus expansion and error distribution width addition explanations. A Force Table Lab where three forces are in equilibrium could use the laws of cosine and sine for the uncertainty estimations of magnitude and direction. This principal factor identification algorithm can be used to describe a critical thinking process. Repeated implementations on a routine basis would take away the creativity or innovative moment encountered in the first realization given an innovative learning example. The subsequent repeated implementations can then be classified as analytical reasoning and calculus rules in long term memory would minimize the demand on working memory.

Another critical thinking process would be an evaluation or synthesis of contributions from competing conflicting factors. In such cases, the project purpose would play an influential role in the formulation of an appropriate measure in the critical thinking process with the details of the mechanism in each factor. An uncertainty estimation of density ρ (Mass/Volume) would have positive contributions from $\delta M/M$ and $\delta V/V$ absolute values for $\delta\rho/\rho$, but a variation in density $d\rho/\rho$ would have positive dM/M term and negative dV/V term when it comes to the question of a targeted density changes. Other examples include the energy conservation application for a system consisted of several masses interacting with contact forces. The maximization of an object's kinetic energy could come from maximizing an external forward pulling force, while decreasing a contact friction force and an external backward pulling force. The variations in calculus representation would have positive and negative terms unlike uncertainty estimation with all positive absolute value terms. A familiarity of elementary calculus in long term memory would enable systematic analytical reasoning without cognitive overload of working memory. A subsequent critical thinking process in the selection of a particular term for modification to satisfice the purpose of cost saving, for example, would avoid memory chunking.

Algebra Working Memory for Physics Learning

The kinematics equation x = v0*(t + 3) + 0.5*(9.8)*(t + 3)*(t + 3) + x0 can be used to illustrate a critical thinking process when the usual time variable is written as (t + 3). When an instructor rearranges the equation in terms of t*t, t, and constant, the term (v0 + something)*t clearly shows an interpretation with a new initial velocity and the constant term is simply indicative of a modified x0. The re-grouping is a critical thinking skill for a student to discover when the negative time solution in v0*(-t) is expressed as (-v0)*t. Likewise an algebraic complex number solution for time of flight, t = P + Q*sqrt(-1) for example, could have a physical interpretation. For an object being thrown upward inside a well of depth -120m under a gravity downward pulling of 9.8 m/s/s, the equation 0 = v0*t + 0.5*9.8*t*t -120 would support a physical situation with a modified depth of (-120 + 0.5*9.8*Q*Q) which carries P as the time of flight since the sqrt(-1) terms must cancel out. Kinematics learning requires a minimum memory capacity when compared to other physics topics. The long term memory of putting the initial numerical values in their appropriate terms could be learned by analyzing each math term in a given equation. The short term memory of keeping track of P and Q are crucial to support the working memory for a critical thinking of a complex number solution. The re-grouping for an interpretation of a modified well-depth when time has a complex number representation would require working memory not tied up by performing simpler tasks achievable by using long term memory. A graph of Q*Q versus well-depth for a given v0 would suggest a maximum physical depth that the object could overcome upon a linear extrapolation to zero Q*Q, shown in Figure 1. An initial velocity of 45 m/s would give an intercept of about 104 m upon extrapolation. The calculus physics aspect is highlighted graphically as well while keeping v0 constant. The understand of a trend would reinforce a physical mechanism for causal reasoning beyond associative learning that a physics exercise is nothing more than a math tool exercise.

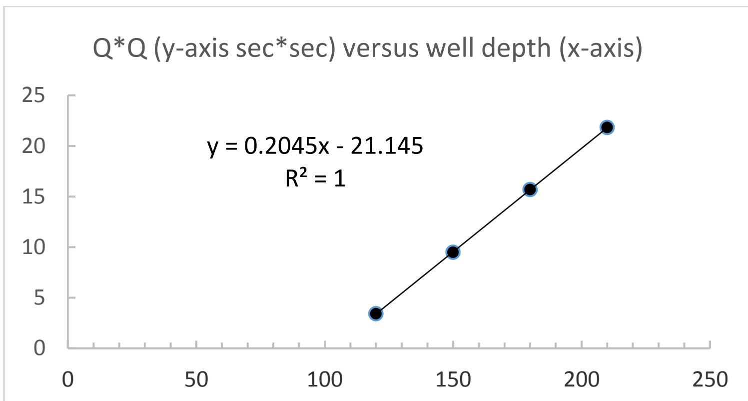

*Figure 1: Q*Q versus well depth for an object thrown upward at 45 m/s.*

The standard math discussion in terms of the parabola vertex distance to the x-axis can also be used in the quadratic equation, $ax^2 + bx + c = 0$, description for the kinematics of throwing an object upward to reach ground level when inside a well[10]. The (4ac - b*b) positive value measures "missing ground level by how much" while b*b = 4ac is the bare minimum case to reach ground level with zero parabola vertex distance. The (b*b - 4ac) positive value measures "overdoing by how much" and points to a quantity that could be used to represent an excess effort in the upward throw for reaching the ground level. Further analytical reasoning development in the (b*b – 4ac) term would lead to energy and work concepts after mass and force were incorporated. The critical thinking for a specific purpose would be used to guide the learning process. Examples such as a minimum speed to maintain a circular orbit, an escape speed for a spacecraft, etc. are critical thinking exercises after the analytical reasoning is developed in the understanding of the mechanism of centripetal acceleration and gravitational attraction. The application of F-net = (mass of system)*acceleration could be used to minimize cognitive loading in setting up the equation of motion without the pulley-torque equation consideration since internal forces come as a pair of equal and opposite forces. A massive pulley contribution to the total mass of a system, consisted of two objects connected by a pulley, can be expressed as the pulley moment of inertia I divided by radius-squared. The parallelism between the translational kinetic energy expression of 0.5*m*v*v and the rotational energy expression of

0.5*I*ω*ω (I as moment of inertia and ω as angular velocity), also help to minimize cognitive loading when using energy concept description for rolling examples.

Spatial Working Memory for Physics Learning

Consistent with an EEG data based report that brain training can boost working memory[11], the verbal working memory and visual-spatial working memory are delineated for brain training in an exercise which carries cloze questions in the first page and numerical calculation questions in the second page. The in-class practice of providing numeracy clarity by an instructor and asking a student for a paragraph describing an associated physical event has been used to help a student to boost up his/her spatial working memory to participate in critical thinking exercises on free body diagrams. For example, the evaluation in the re-grouping of the forces appropriately along an incline plane direction for a simple equation is critical to the success of solving the standard incline physics problem in which one object on the incline was connected to another vertically hanging object. Our assessment data showed that engineering students did well while technology students needed improvement in the cloze question instruction. Our data also showed that the technology students would use associative learning in contrary to causal reasoning used by engineering students, also observed in children learning[12]. The cognitive transformation from causal reasoning to analytical covering several mechanisms, and the development of critical thinking for a specific purpose such as hypothesis formulation are two important issues. For example the analytical reasoning in kinematics, such as the flight time of a football in the vertical direction equation of motion would determine the horizontal range, can be learned and assessed again in collision problem solving using the relative motion concept.

Spatial reasoning has an important application in relative velocity learning and can serve as a valuable tool for assessing causal reasoning capacity. The physics question on an observer moving at an angle would transform a simple 1-Dim collision problem to a 2-Dim collision problem. For example, a moving observer with two orthogonal velocity components would report a 2-Dim collision for the lab frame 1-Dim elastic collision between a 4 kg impactor and the 2 kg target at a total initial energy of 578 Joules. Such a moving observer could adjust his/her velocity such that the total initial kinetic energy equals to 578 Joules, the same value observed by the lab frame observer. A construct of the √Energy or p/√2m variables based on the moving observer's data is shown in Figure 2.

The "e" parameter, which is the height of the 90-degree triangle in the direction of the perpendicular line to the hypotenuse, is shared by both the impactor and the target √Energy variables through the angle θ, shown in Figure 2. An instructor can use the Excel Solver to find such a moving observer with the constraint of 578 Joules as the total initial kinetic energy. The Excel Solver showed that a moving observer in the direction of (-50 degrees) with (9.3653 m/s, -11.1611 m/s) would report a total energy of 578 Joules. The moving observer would report an impactor with velocity component of (7.6347 m/s, 11.1611 m/s) and target with velocity component of (-9.3653 m/s, 11.1611 m/s), given the lab frame of impactor velocity component of (17 m/s, 0 m/s) and target velocity component of (0 m/s, 0 m/s). The moving frame answers could be simply obtained by vector subtraction principle for relative velocity calculation by first year students. After the collision, the lab frame of impactor velocity component (5.667 m/s, 0 m/s) and target velocity component (22.67 m/s, 0 m/s) would transform accordingly for the moving observer. This relative velocity example could be used to assess the cognitive loading of working memory of a student while an instructor could use Excel Solver to generate many different numerical values for student exercises with ease.

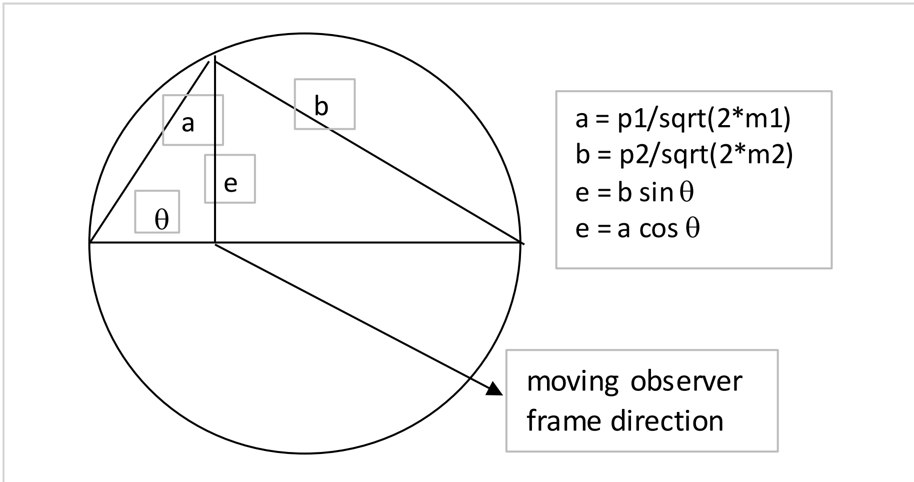

Figure 2: Diagram showing collision variables p / √(2m) seen by a moving observer.

Note that the "e" parameter would be conserved in a collision when an observer moved in a direction of (-45 degree) with (11.333 m/s, -11.333 m/s), and the θ angle of Figure 2 equals 41.8101 degrees. An innovative mindset student would ask for the interpretation of the created "e" parameter. There is an initial "e" value and a final "e" value after the collision. One acceptable answer would be an understanding that the created "e" parameter in the √Energy mathematical space is the result of doing an extension to higher dimension in matrix notation such that an additional parameter would be associated with a 1-Dim collision in the lab frame. The "e" parameter conservation case when the observer moved at -45 degrees direction has a semblance to the Weinberg angle illustration in the merging of electromagnetism with weak interactions[13-14]. A student familiar with geometry would recognize that the θ rotation matrix multiplication is simply equivalent to a rotation of reference axes. The numerical matrix method is effective in generating numerical relative velocity exercises to facilitate teaching. Elastic collision can also be presented as numerical matrix operation[15], which is part of SAT II Math in American high schools[16] and GSCE Math in UK high schools[17]. The collision of an impactor with a target mounted on an oscillatory spring would illustrate that the apparent target mass could increase or decrease according to the phase of the spring oscillation when a collision calculation was done in a target-in-box situation without the knowledge of the spring Coulomb energy. An instructor can use Excel to generate different collision numerical values for different physics classes. The Excel files are downloadable when the article is published[18].

Discussion

Assessment data showed that Electrical Engineering students did well in P + Qi related problems, Mechanical Engineering students did well in rolling motion problems, and Computer Science and Robotics students did well in numerical matrix operation problems. Doing well would be equivalent to less working memory loading and less memory chunking[19]. The converse of "what is in the long term memory" could be used for career discovery when counseling students. Cognitive engaging exercises would produce an encouragement for engineering sub-field selection and assessment data could be personalized to serve as an effective career indicator. The initial enjoyable task of using a high school math tool familiar to the students in their long term memory for physics learning is a practical starting point, consistent with recent neuroscience evidence for the Thorndike's law of effect where a brain would learn to repeat more often when there is a reward[20]. A long term memory related microRNA has been identified for the first time[21], and its gene expression level could be facilitated with the practice of cognitive engaging exercises. Our assessment showed that a critical thinking element is only recognizable after a student could reach the working memory capacity required in the solving of a physics problem. A critical thinking assessment rubric for solving the problem of a moving observer is shown in Table 1. The 2-Dim velocity diagram transformation deliverable would require working memory to process the observer's velocity vector while the momentum and energy conservation equations would rely more on long term memory. The computation of the created "e" values would require the long term memory in trigonometry and working memory of the √Energy (or p/√2m) information processing.

Table 1: A critical thinking assessment rubric.

Deliverable	Highly Competent	Competent	Needs improvement
2-Dim velocity diagram 25%	All velocity vectors are correct	Made one mistake	Made more than one mistake
Momentum conservation (1 Dim and 2-Dim) 25%	All momentum equations and calculations were correct	Corret momentum equations but made one error in calculation	Incorrect momentum equations and/or more than one caculation mistake
Energy conservation 25%	All energy equations and calculation were correct	Corret energy equations but made one error in calculation	Incorrect energy equations and/or more than one caculation mistake
Initial and final created 'e" values (25%)	Correct computation of initial and final created "e" values	Computation less than 10% error	Computation more than 10% error

Conclusions

Assessment data showed the critical thinking element is only recognizable after a student could reach the working memory capacity required in the solving of a physics problem. Future studies on critical thinking improvement could include the use of more innovative computational learning examples, EEG data investigation of working memory training in solving physics problems, ventromedial prefrontal cortex and hippocampus supported abstract memory representations for concept learning[22-23], etc.

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