Teaching students problem solving with the ‘light bulb effect’ cognitive diagrammatic representation

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Abstract. A diagrammatical representation of the cognitive processes required, for solving Physics problems, is used to teach students in Physics I major, at the University of the Witwatersrand, about problem solving by empowering them metacognitively, with the help of a cognitive process diagrammatic representation called ‘the light bulb effect’. After a teaching session on ‘the light bulb effect’ students answer a questionnaire with a problem that is new to them, and then are invited to reflect on their cognitive process by describing those processes in their own words and drawing a ‘light bulb effect’ diagram that represents their cognitive processes. Analysis of responses shows that most students find it easy to describe their cognitive processes after the session and also that students find the session helpful.

1. Introduction

Problem solving ability is one of the most challenging teaching endeavours and yet it is one that is of great importance in physics. True problem solving is a creative process which requires the problem solver to create a path to the solution that is not initially obvious [1]. Problems arise in real life and in physics. In physics, it is used as a learning strategy through which students get the opportunity to practice the principles and concepts they are learning [2]. It is usually only in the process of solving a problem that the true meaning and implication of principles and concepts can be achieved. However, it is usually difficult to teach students the necessary creative processes required for problem solving as most students believe that the required procedure is that of simply remembering the correct path previously demonstrated by a teacher. The student usually obtains this perception from the logical manner in which a teacher presents the solution to a problem in class. This presentation is done with none of the false starts, restarts and rethinking that are usually necessary to create a solution when the problem is a real problem [3]; that is, a problem that the problem solver has never encountered before. Students thus have a tendency to give up when confronting a problem for which they do not have an immediate solution in their memories [2]. But teaching students about the problem solving process, which requires metacognitive monitoring, has been shown to have a positive impact in students’ ability to engage in the required creative problem solving process [4, 5]. Since metacognition involves knowledge and regulation of one’s cognitive processes [6], teaching students about the cognitive processes involved in problem solving and how their cognitive structures form and create meaning should lead to better problem solving performance. The aim of this study is to demonstrate that it is possible to teach students the metacognitive skills involved in problem solving with the aid of the ‘light bulb effect’ diagrammatic representation [7].

The cognitive processes involved in problem solving may be defined as “meaning creation processes” [7]. Incoming stimuli cause neurons or groups of neurons called neural networks to emit signals in reaction to the stimuli. These signals are interpreted by the cognitive system through cognitive structures or cognitive tools that are also made up of neural networks. The cognitive tools grow and change over long periods of time and are what Piaget and Garcia [9] call schema. The development of these cognitive tools or structures is called learning and is a long term process. The cognitive process of creating meaning happens over very short periods, usually within seconds or minutes, and is what Piaget and Garcia [9] call 'assimilation', whilst "accommodation" is the term they use in reference to changes in the cognitive structures or tools. There are three dimensions involved in a cognitive process: the area of content, the level of complexity and time. A student's cognitive structures or tools may be more developed in an area of content, such as in Newton's laws rather than in electrostatics. When neural structures grow in complexity they are able to deal with more abstract processes. For example, a cognitive process, involving arithmetic is more concrete, and therefore less complex than one involving algebra. Students' neural structures need to have developed to the point that they can deal with the abstractness of an algebraic manipulation in order to deal with a problem that requires that level of complexity. It takes time for neural structures to grow in complexity and it takes time for a student to produce meaning in a certain area of content. If the problem is less complex than the students' structures the meaning will emerge much faster than if the problem is far more complex than the cognitive structures that the student has developed up to that point in time [8].

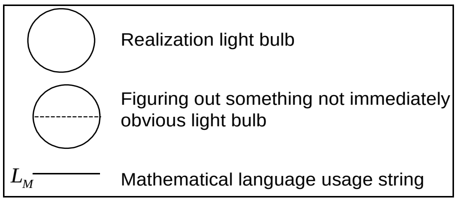

Figure 1. Three diagrammatic problem solving cognitive process representation elements

The 'light bulb effect' was used in 2015 to identify possible processes involved in physics problem solving and to determine which of these processes make a problem more or less difficult for students [7]. In this diagrammatic representation, straight lines, called 'strings' and circles, called 'bulbs', are used to represent different cognitive processes and are linked in a diagram that attempts to represent a complete problem solving process. The strings denoted processes that should have become familiar to the students as a result of use during their school education. The bulbs symbolized processes that would be novel to most students. The two bulb elements and an example of a string element are shown in Figure 1. Each of the string elements were accompanied by a code comprising of a letter and a subscript [7]. Diagrams were assigned levels according to the number of bulbs they contained, so for example a diagram with one bulb was a level 1 (L1) diagram.

The motion of a particle, moving along a straight line is described by the following equation:

$$x = (2.3\ \text{m.s}^{-1})t + (4.8\ \text{m.s}^{-2})t^2$$

where x refers to the particle's position, which is measured in metres, and t refers to time, which is measured in seconds.

(a) What is the particle's initial position at time $t = 0$?
(b) What is the particle's initial speed?

Given: $s = v_o t + \frac{1}{2}at^2$ $\quad v = v_o + at$

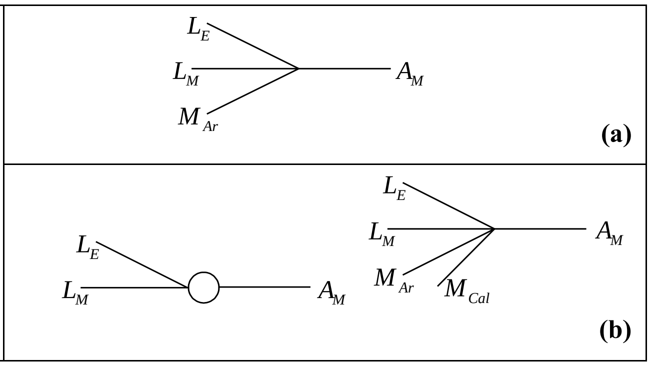

Figure 2. Parts (a) and (b) of Question 2, in the Problem Solving skills test, with the corresponding cognitive process diagrams, appearing on the right.

2. Method and Analysis

In order to demonstrate how the ‘light bulb’ diagrams were used to represent the cognitive processes involved in the solution of a problem, figure 2 shows parts (a) and (b) of question 2 in the Problem Solving skills test, used in 2015, as well as the diagrams representing the cognitive processes they required.

There were two possible diagrams for part (b) because it was discovered after examining the students’ test solutions that some students knew and used calculus instead of going through the ‘light bulb’ process or realization, they would use if calculus was unknown to them. The realization required was that the given expression matched the given equation so that the initial speed could be identified.

Overall, it was possible to conclude that the student performance in questions that required a L1 cognitive process was lower than in the questions where the required cognitive process was at L0 [7], in agreement with the fact that bulbs represent less known processes to the students.

At the beginning of the second semester in 2015, after lectures on Coulomb’s law, the students in Physics I major were given a special presentation on how the brain works and the Light Bulb representation used to analyse the Problem Solving skills test. They were also given feedback on their performance in the test using the analysis previously discussed [7]. During the course of the presentation on how the brain works they were told that at birth the brain is wired already so that stimuli coming in through the senses are connected to certain parts of the brain and over time more and more of these wired connections are used so that networks build up. Then with age and as learning progresses these networks grow larger and more complex. The students were given the following example: When you go to friend’s house for the first time it is sometimes not easy to locate it, you may need to consult the map, count the number of streets and look at the numbers once you get to the right street, whilst feeling uncertain, and it may take a long time to find the right house but as you visit the same friend over and over it becomes easier and takes less time, and you feel more confident. You have now built up a pathway in your brain that helps you find your friend’s house. Then as you continue to visit this friend you get to know the neighbourhood where your friend lives better and so the initial pathway becomes a complex network with you knowing where is the nearest petrol station or local grocery store. Because of this you can now solve more complex problems. Initially the problem was getting to your friend’s house on time, later it may be getting to your friend’s house on time whilst buying bread and filling up with petrol nearby.

The students were encouraged not to give up when solving a difficult problem. The following example was given to them to this effect: Solving a type of problem where there is something you have never encountered before is like standing on the edge of a cliff. You see another cliff on the other side. Between the cliffs there is a very deep canyon which you need to cross - you see no way of crossing. But as you stand there and think about the known paths you took to reach this point and demand of your brain that a way across be found, suddenly, a light bulb rises from the bottom of the canyon, which opens up into a bridge and you walk across triumphantly.

At the end of the session the students were given the Light Bulb Questionnaire. Question 1 in the questionnaire, shown in Figure 4, was a problem that used their recently acquired knowledge of Coulomb’s law but also required a certain realization that the forces between all charges along the sides of the square and Q cancel except for q at the top left and $2q$ at the bottom right..

1. A charge Q is at the centre of a square of side a as shown in the figure below. On each side of the square is a line of charges. Find the magnitude and direction of the electrostatic force on the charge Q.

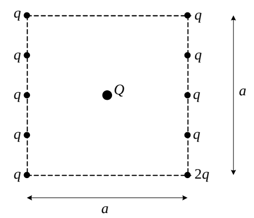

Figure 4. Question 1 in the Light Bulb questionnaire showing a Coulomb’s law problem

The remaining Light Bulb Questionnaire questions are shown in Figure 5.

2. (a) How many realization or figuring light bulbs would you need to represent the cognitive processes needed to solve this problem?
   (b) Describe the process behind each light bulb in your own words:
3. Draw the cognitive process diagram associated to the big problem in question 1.
4. (a) Did you find this teaching session on problem solving helpful?
   (b) Explain why:

Figure 5. Questions 2 to 4 in the Light Bulb Questionnaire

3. Results

Thirty student responses to the Light Bulb questionnaire have been analysed, 27 responses to question 1 showed that students had achieved the intended realization, i.e. all charge contributions except two, cancel. Responses to question 2(a) are summarized in Table 1. Twenty three students thought there were more than 1 light bulb, responses ranged between 2 and 11 light bulbs.

Table 1. Student responses to question 2(a) in the Light Bulb Questionnaire.

Number of students	Number of light bulbs
4	1
23	More than 1
3	No answer

The responses to question 2(b) where students were asked to describe the process behind each light bulb in their own words are summarised in Table 2. All the students who responded could describe their cognitive processes and 20 described 'string' processes as bulb processes.

Table 2. Student responses to question 2(b) in the Light Bulb Questionnaire.

Number of students	**Answer**
17	Described correct realization process
25	Could describe their own cognitive processes
20	Perceived string processes as figuring out light bulbs
11	Described both language and mathematical processes as bulb processes
7	Described mathematical and geometric processes as bulb processes
3	Described understanding language as a bulb processes
4	Described only the intended realization as a bulb process
5	Did not answer

Table 3. Examples of student responses to question 2(b) in the Light Bulb Questionnaire.

Response Category	**Response**
I. Correct realization described as a light bulb (LB)	Figure out that charges q cancel out with the exception of the q at the top and the 2q at the bottom on opposite ends
II. Described understanding language as a LB	*Usually we are given charges with a certain magnitude however in the above problem we are given charges with magnitude q unknown and understanding the given statement about the problem is very important (1st bulb). Hence I felt uncertain on how to solve the problem.
III. Described both understanding language and using mathematics as LBs	Matter of understanding English, physics law, use of mathematical geometry and answering in the form of English physics relationship

Some examples of student responses to question 2(b) are shown in Table 3. The response in the first row is given by a student who described only the intended realization as a light bulb (LB). The response in the row below was made by a student who described the intended realization as a LB but also thought that understanding language was a LB. The last response was given by a student who thought that both language and mathematical processes were LBs.

Table 4: Student responses to question 3, in the Light Bulb Questionnaire

Number of students	**Response**
14	Drew a diagram with only 1 light bulb
1	Drew a diagram with 0 light bulbs
7	Drew a diagram with more than 1 light bulb ranging from 2 to 7
7	Did not answer

Of the 23 students who answered question 3, 22 used realization light bulbs as they had been shown in the presentation. Only 1 student did not, he/she simply made a list of his/her light bulb processes. The number of students drawing diagrams with different numbers of diagrams in response to question 3 is shown in Table 4.

Twenty seven students answered question 4 and 24 said that 'yes' they had found the session helpful. One student said 'a little' and 2 students said 'no'. Both the student who said 'a little' and one who said 'no' in response to question 4(b) wrote that there was something that they had missed in the session. The other student, who said 'no', wrote that he/she didn't think the realization process can be forced or learnt. This student, had the correct realization for question 1, was one of the 4 who in answer to question 2(a) gave 1 as the number of light bulbs needed and also, was one of the 14 who drew a Light Bulb cognitive process diagram with only 1 realization Light Bulb, so perhaps he/she already had the necessary metacognitive skills before the session. Some typical responses to question 4(b) were:

- Very helpful. I never understood why I could 'jam' in some problems, but its just my brain not recognizing the language used
- Realising that the more you use neurological pathways the easier it is to use it. That the only way to create a new pathway is to keep on trying
- Because in a way it gave me an idea or method to do problems and never give up until the bulb glows

In this teaching session students were taught that string processes were processes that were known to them and realization or figuring out processes (bulb processes) were processes that were new to them. But as can be seen from Table 2, many students described string processes as bulb processes. This was probably because these string processes had not developed to the required and expected complexity. For this reason, at the beginning of 2016, Physics I major students were again given a teaching session, a worksheet containing part of the Problem Solving Skills test, and a questionnaire containing a Dimensional Analysis problem instead of the Coulomb problem in the 2015 version, but otherwise the same as the 2015 version. However, this time they were taught that they could use bulbs inserted within strings to represent a string that had to be used at a higher level than usual from the student's perspective. The results from the 10 responses that have been analysed so far are shown in Table 5.

Since all 10 students responded, we see that only 7 students were able to describe their cognitive processes as compared to the 2015 group, where all 25 students were able to do so. Only 1 student drew a bulb at the connection point whilst 8 drew bulbs inside strings. This indicates that students clearly understood that if a string processes was not yet well known it required a realization or figuring out process to use it in solving the problem. The fact that only 1 student used the connection bulb showed that the students focus on the string processes, such as language and algebra, again highlighting the degree of complexity they still needed to develop for these processes.

Table 5. Student responses to questions in the Light Bulb Questionnaire, in 2016.

Number of students	Answer
9	Used the correct realization in solving the problem
7	Could describe their own cognitive processes
3	Described the intended realization
1	Drew diagrams with bulbs at the connection points
8	Drew diagrams with bulbs inside strings
10	Drew diagrams that demonstrated the principles they were taught in the session

4. Discussion and Conclusion

It is encouraging that in the 2015 sample of 30 responses, most students thought that the session was helpful and all who gave an answer (25) could describe their cognitive processes. The fact that so many students, 20, described 'string' processes as bulb processes suggested that their cognitive tools had not developed enough complexity for their use to be easier. This indicates more learning needs to occur in these areas. The fact that so many could describe their cognitive processes and from the mainly positive responses to question 4 means that metacognitive understanding was imparted in the session to the majority of these thirty students. Even though metacognitive understanding was clearly also imparted in 2016, the results show that less students learnt to describe their cognitive processes. So it can be concluded that giving the students a test and giving them feedback thereafter, showing them how the 'light bulb' representation works, as was done in 2015, is the superior way of using the "light bulb effect' for teaching students about the cognitive skills involved in problem solving.

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