

Revisiting the Cognitive Processes of the Brainstorming Technique: Theoretical Considerations from a Synthesis of Piaget, Vygotsky and SIAM for Learning Science

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Abstract: Brainstorming is not new and has been used in teaching and learning for many years. However, how this technique leads to learning is still vague. In this paper the authors first put forward extended procedural steps to the basic brainstorming technique. The cognitive processes associated with the brainstorming technique include creative and critical thinking and problem solving skills. The authors argue a possible theoretical position for these cognitive processes underlying the procedural steps of the brainstorming technique in the science classroom and how learning could occur during utilization of the brainstorming technique in teaching and learning science. The cognitive theories employed for the underlying theoretical framework are: Search for Idea in Associative Memory (SIAM) theory, Piaget's Cognitive Development theory, and Vygotsky's Socio-cultural theory.

Keywords: Brainstorming technique, SIAM, Piaget, Vygotsky

I. INTRODUCTION

Osborn (1953) introduced brainstorming as a technique to increase group creativity. However, he did not provide a theoretical basis for the brainstorming technique (Butler & Kline, 1998). Nevertheless, there are a few empirical studies that offer an evidence base for understanding how brainstorming leads to learning (Wang, Rosé, & Chang, 2011). Wood (1970) showed that the brainstorming technique of problem solving has much merit, as it makes learning an active process. The learner will have fun and soon will become very skilled and perceptive in the science. According to (Davis, 1986) brainstorming has great importance in the teaching process and the development of creative thinking, critical thinking and problem-solving skills among students, as it helps students to learn because there are no rules, criticism or evaluation to restrict the production of ideas. In addition to this, brainstorming is in a way a training process to stimulate cognitive processes for imagination and flexibility in creative thinking. In addition, Conklin (2007) stated that traditional teaching methods are not effective and more teachers should use interactive methods such as the brainstorming technique which can enable students to construct knowledge and improve mental abilities. Enhanced performance due to cognitive stimulation and cooperative learning in group brainstorming has been found (Paulus & Yang, 2000).

DeHaan (2009) demonstrated that brainstorming provides an opportunity for teachers to pose a problem and to ask the students to suggest as many solutions as possible in a brief period, thus enhancing ideational fluency. Here, students can be encouraged explicitly to build on the ideas of others and to think flexibly. Mohammed, (2010) asserted that the brainstorming technique provides an opportunity for a learner to impose assumptions, observe, experiment, measure, and infer.

Wang et al. (2011) showed that the brainstorming technique is beneficial for students' learning in science education. The learning through brainstorming comes from the cognitive, inferential process of idea generation, building on prior knowledge as well as from the collaborative process of students' building on one another's ideas. These components of cognitive and collaborative processes make brainstorming a powerful technique for students' learning and teachers teaching. In more recent studies, (Mased & Yamin, 2012; Mohammed, 2010) have stated that critical-thinking ability is stimulated in brainstorming, through the process of problem solving, particularly in evaluation and the selection ideas

stage when group brainstorming discussion critically considers one best possible solution for the problem. Overall, brainstorming has been found to improve creative thinking skills, critical thinking skills, problem-solving skills, and achievement among learners, as well as improving the attitude of learners towards science learning (Cheng, 2011; Fanona, 2012).

II. BRAINSTORMING FOR PROBLEM SOLVING, CREATIVE AND CRITICAL THINKING IN THE SCIENCE CLASSROOM

Several researchers have highlighted the effectiveness of brainstorming in teaching and learning (Butler & Kline, 1998; Cheng, 2004, 2011; DeHaan, 2009; Harbi, 2002; Hobson, 2001; Holubová, 2010; Jessop, 2002; Mased & Yamin, 2012; Paulus & Paulus, 1997; Wang, Rosé, Li, & Chang, 2006; Wood, 1970) and is illustrated in Table 1.

TABLE 1: PAST STUDIES RELATED TO THE BRAINSTORMING TECHNIQUE

| Author | Year | Contents |
|-----------------|------|--|
| Wood | 1970 | Brainstorming an effective teaching technique for all levels of learning. |
| Paulus & Paulus | 1997 | Group brainstorming increase productivity, learning, and creativity for gifted and regular education. |
| Butter & Kline | 1998 | A comparison of brainstorming, hierarchical, and changing perspective to determine which produced the most, best, and the most creative solutions. |
| Hobson | 2001 | Using brainstorming as an interactive technique for teaching physics. |
| Harbi | 2002 | Brainstorming develops critical thinking skills and academic achievement in biology lessons. |
| Jessop | 2002 | Brainstorming and critical thinking skills to expanding students' brainpower in chemical and biochemical engineering. |
| Cheng | 2004 | Enhancing creativity in physics by using brainstorming technique and other different strategies. |
| Wang et al | 2006 | Virtual brainstorming to support productive group for collaborative creative idea generation in science education. |
| Alaatari | 2006 | using brainstorming method in teaching science on developing the creative thinking of the second grade intermediate pupils in Arar City |
| DeHaan | 2009 | Using brainstorming technique to promote creative problem solving in science. |
| Holubova | 2010 | The effectiveness of brainstorming technique as modern teaching methods in teaching physics. |
| Mohammed | 2010 | Using brainstorming for developing science processes skills among fifth secondary students in biology. |
| Chang | 2011 | Brainstorming technique for infusing creativity into regular science lessons. |
| Fanona | 2012 | Using brainstorming in the development of concepts and the attitude towards biology for the eleventh grade Male students. |
| Mased & Yamin | 2012 | A comparison of problem based learning and brainstorming technique on developing critical thinking. |

Brainstorming is a type of stimulation to activate particular cognitive structures (relevant domain knowledge) in the mind of students for in-depth search (deep exploration) for creative idea generation (Stroebe, Nijstad, & Rietzschel, 2010). The most important function of the brainstorming technique for students is to practice the flexibility, fluency, risk taking, elaboration and other skills, which are associated with creativity (Starko, 2009). The main purpose of brainstorming is to let students generate ideas or options for solving a problem by themselves (Wang, et al., 2006). Butler and Kline, (1998) found that brainstorming is an effective technique for facilitating intellectual fluency to help students generate creative solutions. Cheng (2011) found that in addition to creativity enhancement, brainstorming improves students' abilities, of

novel and innovative thinking, challenging and risk-taking attitudes, metacognition, understanding of science knowledge and positive attitudes towards science learning.

Schneider, (2002) asserted that brainstorming is an effective technique to develop and enhance critical thinking skills for students in science, as it helps activate student’s thinking to explore new options instead of merely receiving information from a teacher. Harbi (2002) identified brainstorming as a useful method for developing critical thinking and that there is positive and direct statistically significant relationship between critical thinking and achievement when using the brainstorming technique among biology students in a secondary school. Brainstorming develops critical thinking when students working in-groups begin to evaluate each generated idea using agreed-upon criteria. Students will discuss whether or not their proposed ideas were likely to solve the problem and decide which ideas are to be rejected and which ideas are to be modified to make them more powerful and appropriate to solve the problem (Case, 2005; Mased & Yamin, 2012). Ho, (1998) found that ideas generated during brainstorming become more effective and feasible when group members evaluate and judge it. Creative and critical thinking can be said to have three dimensions: the analytic, the evaluative, and the synthesis (creative), these three dimensions cannot be separated from each other and must be involved together to be effective (Paul & Elder, 2008). Lamb, (2003) and Huitt, (1998) equate evaluation with critical thinking and synthesis with creative thinking.

Enhancing thinking skills (Mestre, Dufresne, Gerace, Hardiman, & Tougher, 1992), Rabari, et al., 2011) is an important aim for science education. Therefore, many researchers have made connections between critical thinking and creativity (Aizikovitsh-Udi & Amit, 2011; Bailin, 2002; Barak & Dori, 2009; Bonk & Smith, 1998; Cotton, 1991; Fisher, 2002; Forrester, 2008; Glassner & Schwarz, 2007; Harris, 1998; Koh, 2002; Marrapodi & Education, 2003; Paul & Elder, 2008; Rabari, Indoshi, & Okwach, 2011; Sulaiman, 2011; Swartz, Fischer, & Parks, 1998); Glassner & Schwarz,2006). All researchers agree that students need the process of solving the problem for both creative and critical thinking. This is because first, students must analyse the problem, then generate possible solutions, next choose and implement the best solution, and finally, evaluate the effectiveness of the solution. In this manner, there is a resonance between creative and critical thought (Bacanli, Dombayci, Demir, & Tarhan, 2011).

Fisher (2002) defined that the right brain represents creative thinking and the left brain represents critical thinking. Fisher, (2002), Glassner and Schwarz, (2007) and Harris, (1998) have differentiated between critical thinking, which is described as being left brained, analytical, convergent, vertical probability, making judgments, hypothesis testing, objective, closed and linear, reasoning, logical; and creative thinking, which is characterized as being right brained, generative, divergent, lateral possibility, suspended judgment, hypothesis forming, subjective, open-ended, associative, speculative, and intuitive. The brainstorming technique (which can be seen as an educational stimuli) stimulates both the left and right sides of the brain during the learning process to produce ideas to cope with the situation and restore equilibrium during problem solving (Fanona, 2012).

To summarize the ideas of how brainstorming encompasses problem solving, creative and critical thinking have been researched and discussed by various researchers, Figure 1 below is put forward by the authors to indicate the cognitive processes associated with brainstorming.

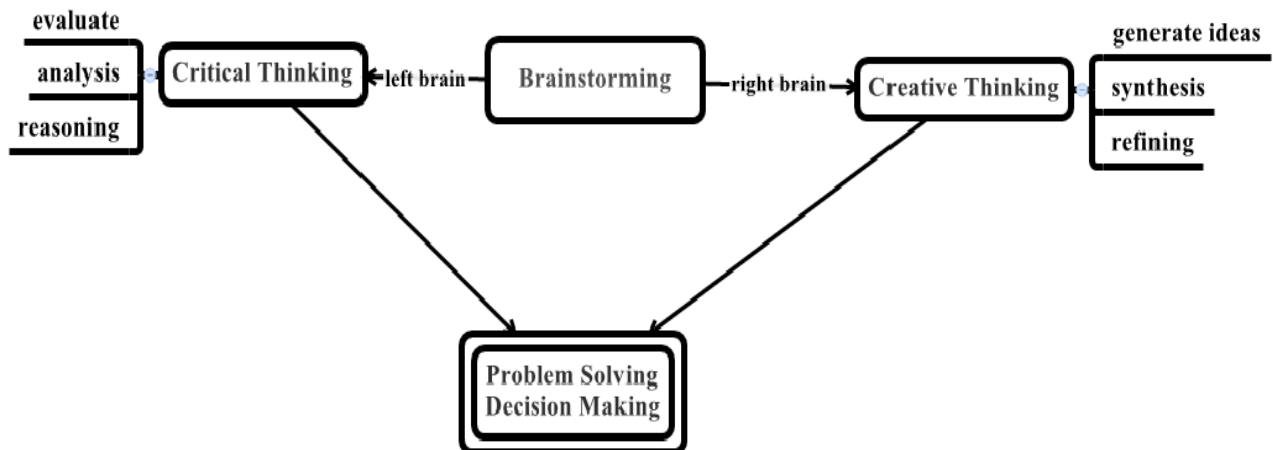


FIGURE 1: Error! No text of specified style in document.: The Brainstorming technique for problem solving, creative and critical thought

III. COGNITIVE PROCESSES AND STAGES OF BRAINSTORMING IN THE SCIENCE CLASSROOM

The brainstorming procedure was designed with the specific goal of stimulating thinking skills to solve problems. Brainstorming procedures make students spend their time thinking about and organizing the salient concepts or points of the topic instead of simply recording information and listening (Seeler, Turnwald, & Bull, 1994). However, in order to activate student's mental abilities, brainstorming follows three stages, namely problem identification, idea generation and idea evaluation. The authors have illustrated the stages of the brainstorming technique in Figure 2.

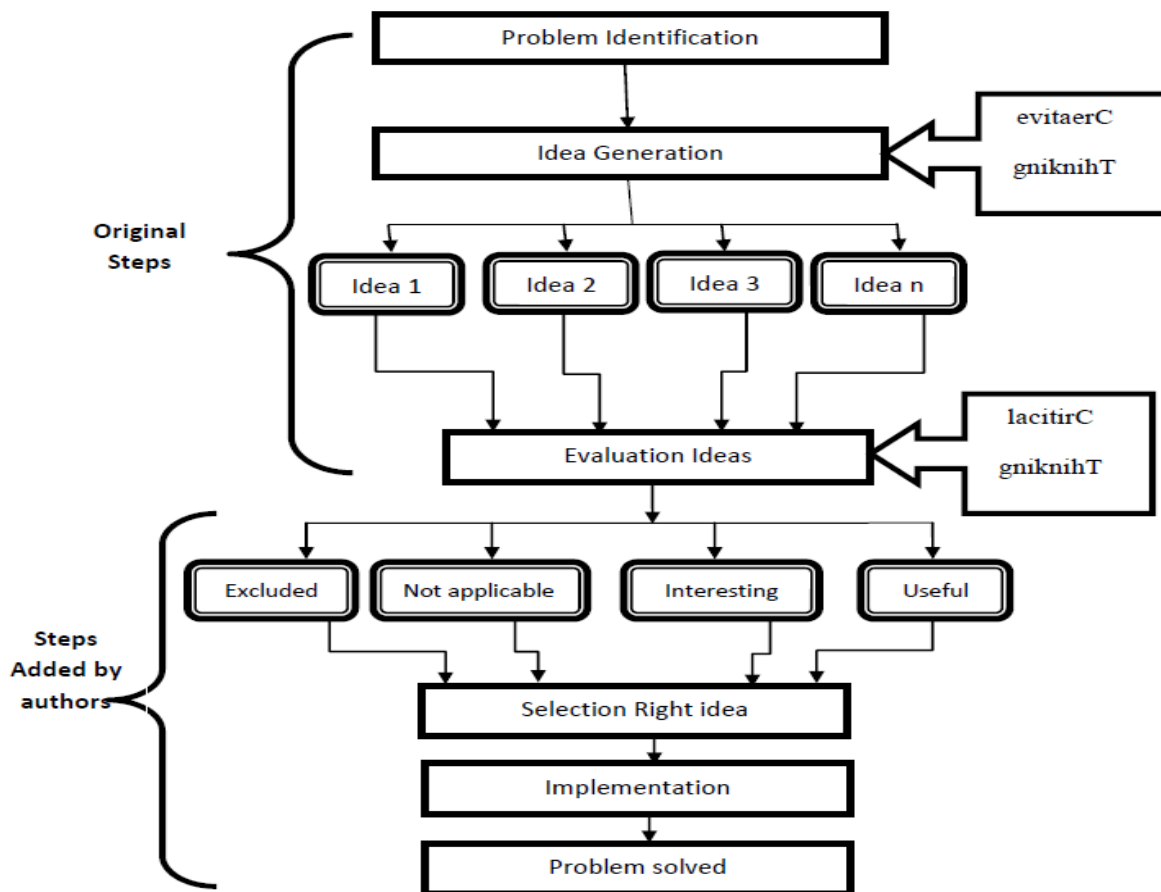


FIGURE 2: Cognitive Processes and the Stages of Brainstorming

The first stage “identification of the problem”, is the key to generating a great number of ideas. Dewey, (1903), the philosopher, commented that “a problem well-stated is a problem half-solved.” Brainstorming is intended to open fresh perspectives and allow learners to attack the original problem from a new point of view. For this to be effective, students must be able to understand the problem, understand abstract principles for reversing data, and to use them in a new situation (Starko, 2009). A good problem should be presented with questions such as, What is the purpose? Why is this important? Who is affected? and so forth. These types of questions would help learners to activate prior knowledge and generate more ideas. In essence, by clearly viewing the problem from all angles, it is easier to start the brainstorming process. It is also imperative when brainstorming in a group that all members understand the questions to the answered before suggesting solutions. If some group members misinterpret the problem, they will not be contributing to the solution, and they may slow down the brainstorming process.

The second stage is the actual brainstorming for the generation of solutions (ideas). During the generative process, learners would probably activate the right brain (divergent thinking) to generate and to synthesise a set of novel mental models as potential solutions to the problem by linking new knowledge with old knowledge or making connections between various concepts (DeHaan, 2009). Critical restraints are minimized to encourage free creativity in generating lots of ideas and building upon one another’s ideas (in group brainstorming) to generate even more ideas. Students can think

freely, by consciously trying to see in a new way, to imagine new possibilities without critical restrictions, because they have the security of knowing that their wild ideas will be critically evaluated during the evaluative phase that follows (Rusbult, 1997).

The third stage is the evaluation of ideas. The first step of evaluation is simply to choose ideas, which are potential solutions for the problem. In this stage, a learner would employ critical thinking abilities (convergent thinking) to analyze and evaluate each idea to ensure the ideas would actually be useful or effective in some way. Only at this time are similar ideas combined, criteria for judging the ideas determined, and the best ideas would be selected (Finney, 2008).

The authors have extended another final stage which involves acting and selecting upon the best ideas and evaluating the results, for example run the experiment and determine if the hypothesis is proven or not (Jessop, 2002). In this stage, a learner needs to blend between creative and critical thinking to solve the problem.

IV. BRAINSTORMING AND LEARNING THEORIES

Three cognitive theories are suggested in this paper to explain the cognitive processes underlying brainstorming and how learning occurs during utilization of the brainstorming technique. These theories are: Search for Idea in Associative Memory (SIAM) theory (Nijstad, 2000; Nijstad, Stroebe, & Lodewijckx, 2002, 2003), Piaget's Cognitive Development theory (1929), and Vygotsky's Socio-cultural theory (1978). All these theories play an important role in explaining how knowledge is generated and how learning occurs during brainstorming.

SIAM

Search of ideas in associative memory (SIAM) is a cognitive theory developed to explain the cognitive processes underlying idea generation in the brainstorming technique. It is an extension of Raaijmakers and Shiffrin (1981) Search of Associative Memory (SAM) model of memory retrieval. The SAM model explains that learning occurs from the short-term memory control process (coding, rehearsal and decision) and retrieval of a variety of long-term memory structures followed by the formation of new associative relationships between the retrieved structures. SIAM is similar with the SAM model and assumes that there are two memory systems: short-term memory and long-term memory (Nijstad, 2000; Nijstad & Stroebe, 2006; Nijstad, Stroebe, & Lodewijckx, 2002, 2003).

1. Short-Term Memory

Or called a limited capacity Working Memory (WM), working memory can only handle a small number of "units" or "chunks" at one time. It is labile, often lasting only a few seconds without specific activities to prolong it. The major role of WM is used as a working space for control processes of all sorts, including plans, coding, rehearsal, and decision.

2. Long-Term Memory (LTM)

An unlimited capacity consists of elements that are a richly interconnected network of cognitive nodes that is called a (semantic network). Long-term memory contains a vast quantity of relationships, schemes, frames, and rules for how to use and process them (declarative and implicit memory). It is highly stable and can store data for decades. However, long-term memory for science learning is not just having the memory, but being able to use it and make the associations that bring it into working memory. This is important for students to understand knowledge of science to be functional.

SIAM assumes that LTM and WM memory are essential elements of the brainstorming process because brainstorming repeatedly searches for ideas in associative memory and their integration in working memory. How can this be visualized? As stated earlier, the first stage of the brainstorming technique is identification of the problem. During problem identification activation and retrieval of prior knowledge (image, concept or idea activation) in LTM occurs. This activation of knowledge is a controlled process in which search cues are applied, which image or concept is activated is probabilistic and depends on the strength of association between the search cue and the concept. Concepts that are more similar to one another have many strong connections with currently active ideas than concepts which are very different from one another. When a particular idea or concept is activated other ideas or concepts with strong connection to that idea are also activated. Consequently, these are analyzed automatically in series on stages along many parallel paths (Dugosh, Paulus, Roland, & Yang, 2000). This analysis results in activation of information in LTM.

An example is given in Figure 3. The initial stage for knowledge retrieval is that the science teacher should stimulate students for activation of a particular knowledge by identifying a problem as a question to guide students for a retrieval plan of knowledge from LTM to answer the question.



Why does the pen appear broken when you look at the surface of the water cup?

FIGURE 3: An example of a science problem

The retrieval plan includes an initial decision such as what is the scientific law that should be employed to solve the problem and what combinations of probe cues should be employed. The teacher can facilitate the students to ask questions such as,

“What is the phenomenon that explains the problem?”

“What is the relevant information to this problem?”

Next, basic to the retrieval plan, the probe cues of information have to be assembled in WM to be used in retrieval of knowledge from LTM. Generally, these cues will include information related to the science problem. Following this, the retrieval process concerns searching for knowledge, determining relative knowledge and recovery from LTM. These three steps will determine what image is sampled and how much of the information in the sampled image becomes available to the problem. Finally, when the recovery process has brought enough information to solve the problem, this information will be subject to evaluation and decision-making. The evaluation stage includes deciding whether the sampled information was indeed on the list being tested, whether the sampled image matches the problem, whether a response should be output (knowledge has been activated), and whether the research should be continued. If the research is continued the process loops back to the retrieval plan to start the next step in the retrieval process.

According to the SIAM theory when the knowledge has been activated in LTM the second stage of brainstorming technique which is idea generation can proceed. Knowledge activation in LTM is thought to stimulate the learner’s mind to activate the creative thinking skills to construct new ideas by connecting new knowledge with the old, build new links, rearrange or reverse knowledge, build connections between various concepts, form new associations, or apply knowledge to a new domain in order for the learner to attain equilibrium. A single initial idea can be used to generate further varied ideas and thus these should be semantically more closely related than ideas which develop from differing initial ideas. These ideas can be added to the search cue to activate new ideas in LTM. This could result in a “train of thought” a rapid accumulation of semantically related ideas. When a train of thought no longer leads to new ideas, a new search cue must be assembled, a process which takes some time. The new cue is then used to probe memory and results in the continuous activation of new images and the generation of additional ideas (Brown & Paulus, 2002; Nijstad, et al., 2003).

The evaluation stage employs critical thinking to decide whether the ideas generated match the problem, whether a response should be the output (ideas to be implemented), and whether the search should be continued. If the search is continued the process loops back to the search of knowledge in LTM to start the next step in the knowledge activation. The authors have put forward the ideas above in Figures 4 and 5 to illustrate the process of knowledge activation in LTM as well as the process of idea generation for the brainstorming technique. After the ideas have been evaluated the group members begin to implement the ideas to solve the given science problem.

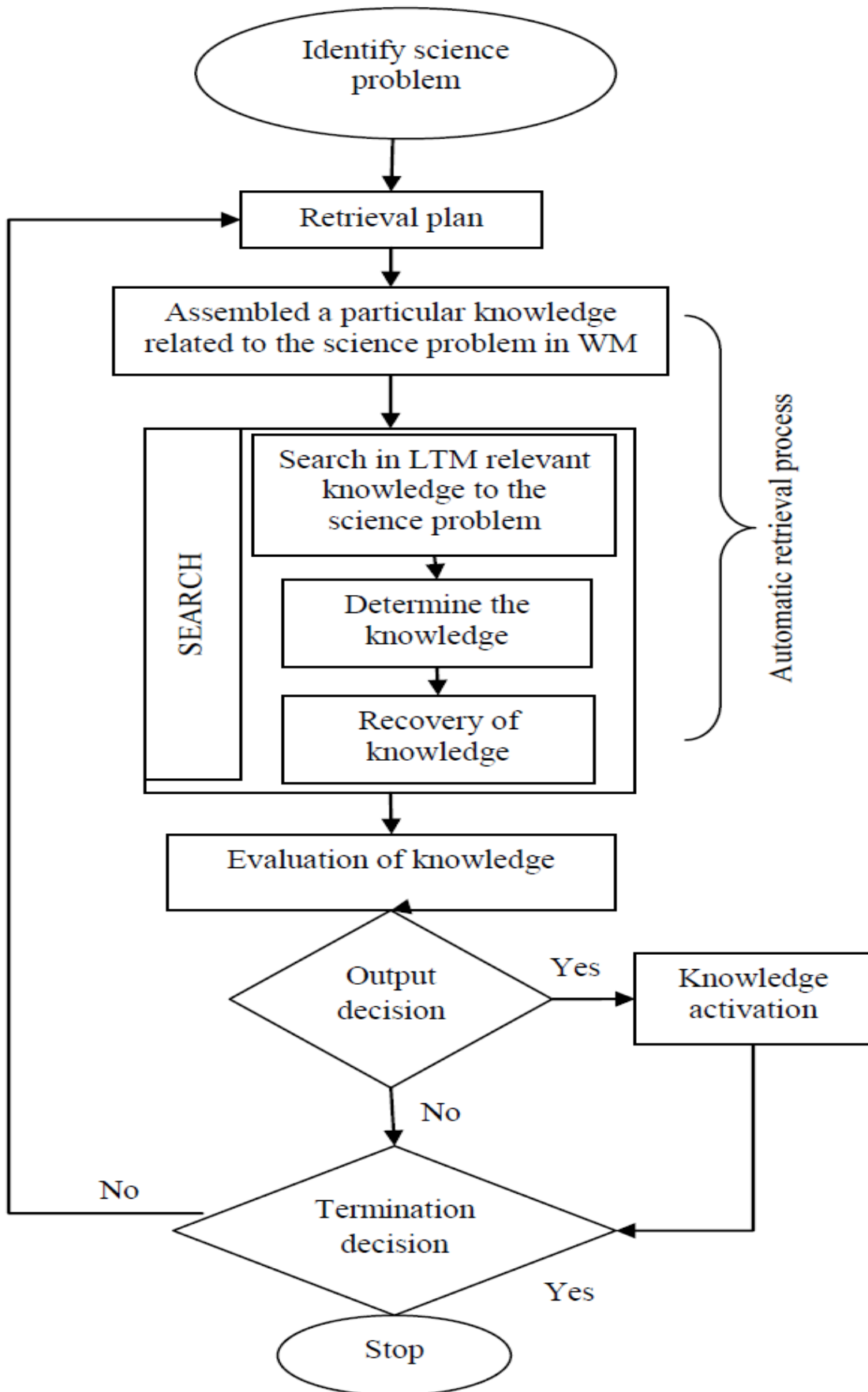


FIGURE 4: Knowledge activation from Raaijmakers and Shiffrin, (1981)

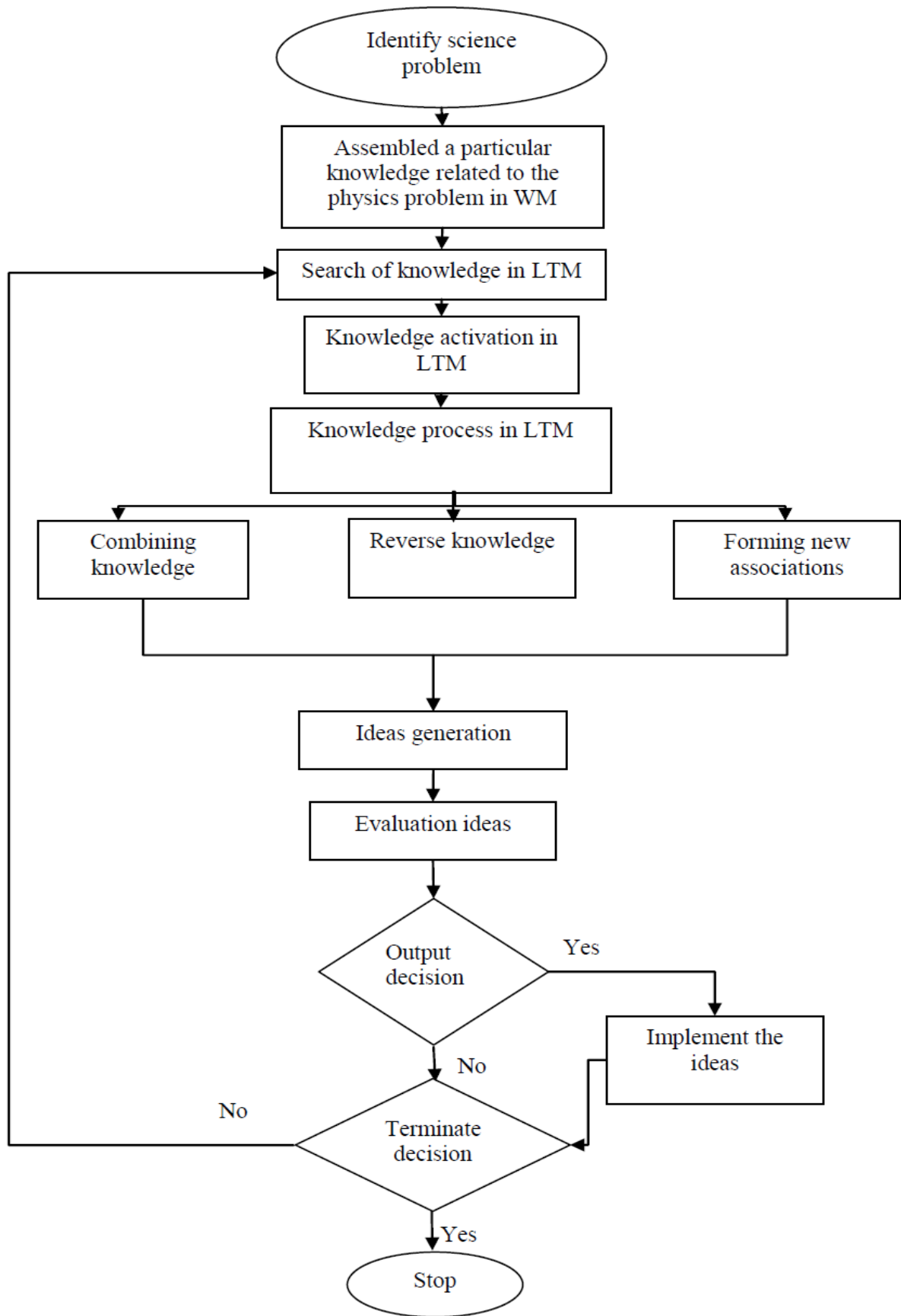


FIGURE 5: Ideas Generation for the Brainstorming Technique

V. PIAGET’S COGNITIVE THEORY (1929)

Piaget (1929) saw learning as the process of creation and innovation. Piaget believed that the process of thinking (creative and critical) and learning requires four processes:

Schema: Mental structures which organize past experiences and provide a way of understanding future experiences.

Assimilation: Incorporate new information into existing schemas. In other words, the process of modified experience and new information to suit what an individual knows in advance, and occurs when the individual is facing a new situation and tries to modify the experience with the appropriate the cognitive structure, it is a process of changing experiences to become familiar.

Accommodation: A mental process that restructures existing schemas so that the new information is better understood.

Equilibrium: The process of seeking mental balance. Piaget believed that equilibrium and disequilibrium occurs when the learner tries to look for existing knowledge incompatible with the new experience of the individual. The more times the equilibrium of the student is lost and then restored, the better the learner’s ability to cope with new situations. Equilibrium influences schemas because of the internal and external processes through assimilation and accommodation.

Mutual stimulation within the brainstorming processes increases the likelihood of cognitive conflict. Cognitive conflict is the mental state in which learners become conscious of gaps in their understanding, which increases their receptivity to cognitive restructuring and learning. The brainstorming process forces students to develop existing schemas and create new structures. Hence, student would actively seek re-equilibrium when he/she faces a new science problem. The learner internalizes hypothetical-deductive question asking and generates answers which involve the acquisition of linguistic skills associated with hypothesis testing and leads ultimately to the development of hypothesis testing schemes and patterns of discussion with his/ her group member if his answers are correct or not. The learner must rely on others for this so when left on his/her own he/she simply generates ideas and for the most part, uses them for better or for worse. At this point, a successful assimilation has occurred. When assimilation is accomplished by the learner, he/she would refine and be ready to solve the physics problem. As a result, students would attain equilibrium again.

In contrast, if new knowledge cannot be linked to the schemas that are already available in the learner’s mind, students who go through the active phase of the brainstorming procedural steps would discuss and analyze the science problem with his/her group to stimulate their minds for employing creative thinking to generate and hypothesize ideas by combining new knowledge with the old, forming new associations, rearranging or reversing knowledge for solving the given science problems. Following this, students will activate the critical thinking to evaluate each other’s ideas together and select one right idea to apply in solving the science problem. At this point, a successful accommodation has occurred. As a result, students would achieve mental equilibrium. In summary, a series of assimilation and accommodation are continuous during the brainstorming session until the learner implements the right idea to solve the science problems. At this point, learners reach mental equilibrium and develop his\her schemas. The authors have interpreted Piaget’s theory during the brainstorming technique in the classroom as in Figure 6.

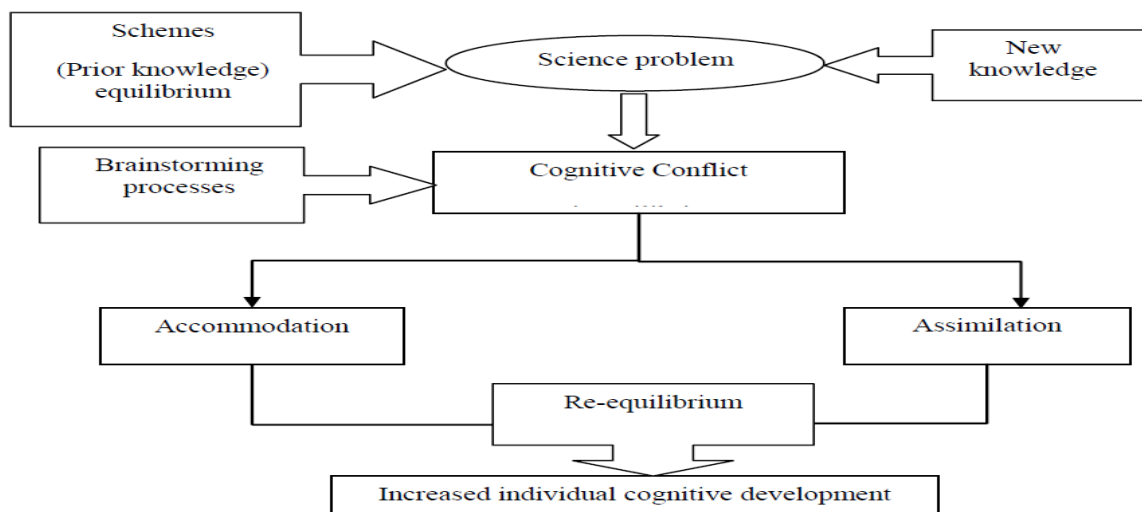


FIGURE 6: Interpretation of Piaget’s Theory for Brainstorming (1929)

VI. VYGOTSKY'S SOCIO-CULTURAL THEORY (1978)

Vygotsky had developed a socio-cultural approach to cognitive development. Individual development cannot be understood without reference to the social and cultural context within which it is embedded. Higher mental processes (creative and critical thinking) in the individual have their origins in social processes. The individual cannot learn and develop higher mental skills without communication from others. Vygotsky (1978) believed that learning always precedes development along the ZPD. The Zone of Proximal Development (ZPD) is “the distance between the actual developmental level as determined by independent problem-solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers” p86.

Scaffolding is the support given during the learning process which is tailored to the needs of the student with the intention of helping the student achieve his/her learning goals via focused questions and positive interactions. Individualized supports, such as small-group learning, can be provided. The idea is to build on prior knowledge with the teacher supporting the learner's development to get to the next level and reduces uncertainty or difficulties so learning is maximized.

The students need assistance (scaffolding) to solve the science problem during the brainstorming procedure. Therefore, the teacher could facilitate the learning process and scaffold the learner by: -

- i. Working collaboratively within a group;
- ii. Identifying a good problem to stimulate the mind of students;
- iii. Encourage members of the group to discuss and dialogue;
- iv. Provide each learner paper to write down ideas for solving the problem;
- v. Instruct students to analyze the problem by dividing it to the sub-problem;
- vi. Instruct students to synthesize and organize the information and
- vii. Instruct students to discuss and evaluate the result

Thus, it can be said that the mutual stimulation during group brainstorming helps students to generate new ideas and develop creative thinking skills. Listening to other students' ideas provokes thinking and draws attention to different aspects that may not have come to mind before. This stimulation can cause students to listen to the ideas of others viewed from angles other than their own. Providing an opportunity for students to exchange ideas, modify existing ideas and adding to the existing information could also allow an increase in student activity that can influence each other, as participants within a brainstorming group possess a huge pool of knowledge as they are from a variety of backgrounds.

Evaluation during brainstorming procedures encourage students to use higher thinking skills (such as analysis and synthesis) through dialogue and discussion of generated ideas, considering divergent views from the members of group, exclusion of incorrect ideas, complete incomplete ideas and then trying to agree on one point of view (ideas) to be adopted as the answer to the problem including providing appropriate interpretations as to the choice of the idea. Successful scaffolding results in increased cognitive development for learners and develops creativity, critical thinking and problem-solving skills. The authors have interpreted Vygotsky's theory during brainstorming in the classroom as illustrated in Figure 7.

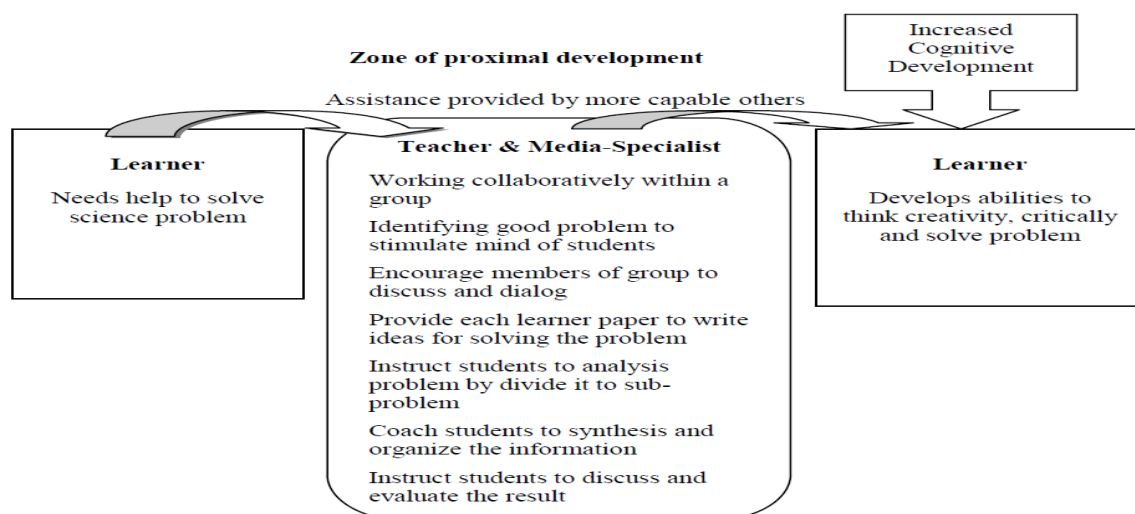


FIGURE 7: Interpretation of Vygotsky's theory for Brainstorming (1978)

VII. SYNTHESIS OF SIAM, PIAGET AND VYGOTSKY

The authors have synthesized and interpreted the three cognitive theories: Search of Ideas in Associative Memory (SIAM) theory (2003), Piaget’s cognitive development theory (1929) and Vygotsky social-cultural theory (1978). The SIAM theory shows how a learner retrieves knowledge from LTM and how a learner generates ideas; whereas Piaget’s theory shows how a learner reaches, mental equilibrium and develops his/her cognitive structures. Lastly, Vygotsky’s theory shows how teachers and peers could assist a learner to develop abilities to think creativity, critically and solve the problems. Figure 8 illustrates the cognitive processes interpreted by the authors for a learner during brainstorming technique by interpreting and synthesizing the (SIAM) theory (2003), Piaget’s cognitive development theory (1929) and Vygotsky social-cultural theory (1978).

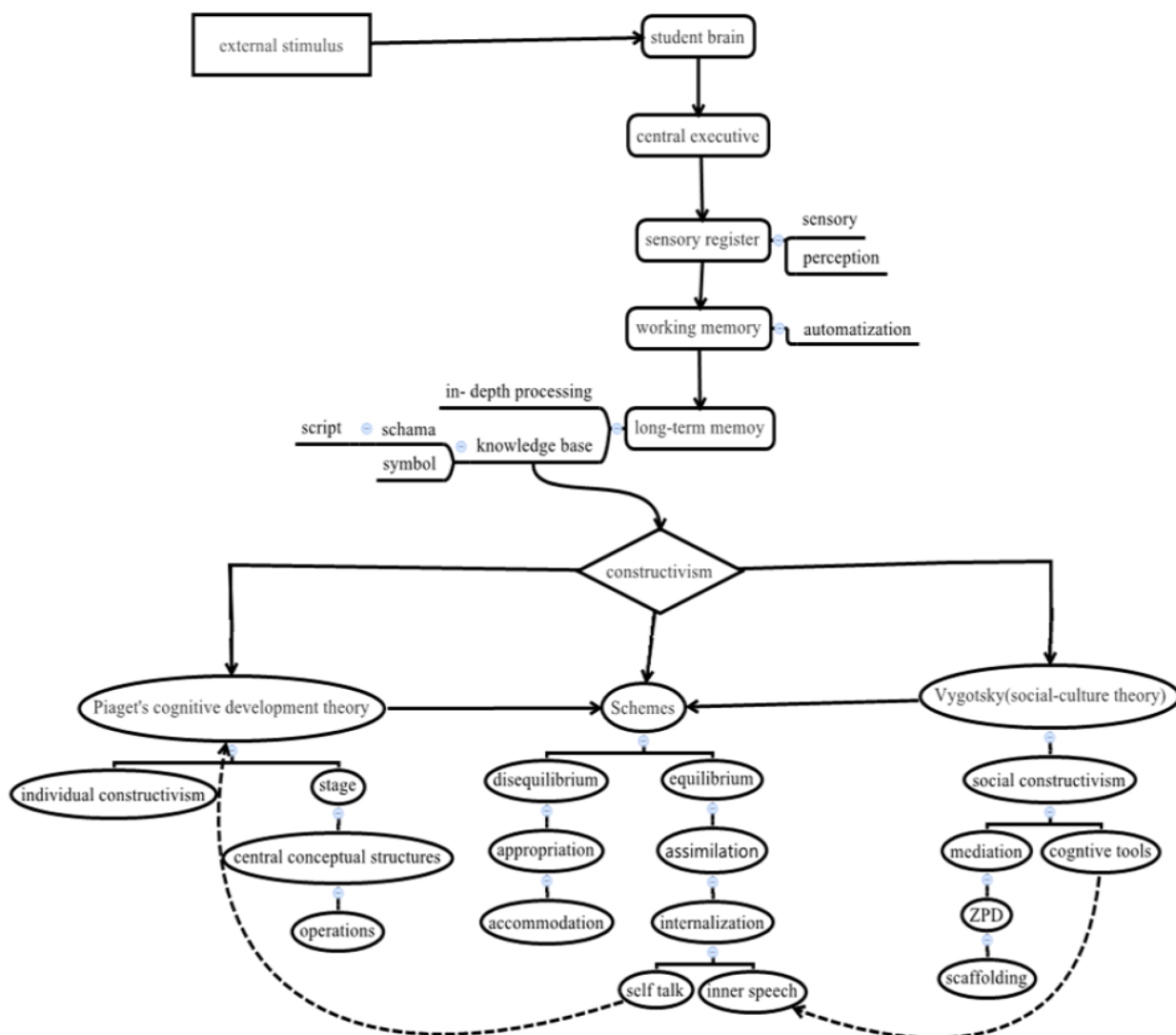


FIGURE 8: Interpretation of the cognitive process for students during brainstorming technique

VIII. CONCLUSION

The brainstorming technique continues to be widely applied for teaching science in many empirical studies. However, none of these studies have explicitly explained how brainstorming leads to learning. Therefore, the major motivation behind this paper was to provide an explanation for the cognitive processes underlying brainstorming as a technique for teaching science. Three cognitive theories were synthesised to explain and to help visualise that procedures of the brainstorming technique could actually stimulate three main thinking skills: problem solving, creative and critical thinking skills among science students.

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