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Analysis of the Scientific Imagination Process

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ABSTRACT

Scientific inventions arise from the exercise of a rich imagination. This study aimed to explore the mechanisms and factors influencing the Scientific Imagination Process of elementary school students. Five award-winning science teachers and nine students recruited from a southern city of Taiwan participated in this study. The five teachers had an average seniority of 24.6 years and had won numerous major awards in the International Exhibition for Young Inventors (IEYI). The nine students had been instructed by these teachers with regard to their entries to the IEYI. Data were collected via teacher interviews, student interviews, and classroom observations. Data were analysed using qualitative methods and coded using ATLAS.ti software. This study provided multiple forms of evidence to ensure research validity. The results identified three stages in the Scientific Imagination Process: Initiation Stage, Dynamic Adjustment Stage, and Virtual Implementation Stage. Each stage was found to have its own key components. Additionally, individuals were influenced by both internal (e.g., motivation and personal dispositions) and external (e.g., family environment, teacher guidance, peer interactions, and multiple life experiences) factors during the process of scientific imagination. Several implications and suggestions for further research were also discussed.

Imagination is more important than knowledge

~ Albert Einstein

1. Introduction

1.1. Scientific invention and imagination

Scientific inventions arise from the exercise of a rich imagination. Indeed, imagination is the driving force behind human thought, and human civilisation is created by the operation and exercise of imagination. Current developments in scientific technologies are the best examples of the process leading from the concretisation of imagination to the demonstration of creativity (Vygotsky, 1930/2004). From Cai Lun's invention of paper during the Eastern Han dynasty in AD 105 and the Chinese invention of printing technology in AD 550 to the invention of computers in AD 1946 and the development of the Internet in recent years, all great inventions originated from human imagination. Human beings use imagination to construct scientific theories and create new inventions to improve life through the process of constant thinking and trial and error. For example, Albert Einstein famously imagined himself flying at light speed and visualised the objects that he might see; from that flight of fancy and following further thought and verification, he ultimately developed the theory of general relativity. Thomas Edison invented light bulbs by imagining the use of many different materials for filaments and

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through many repetitive tests. The imaginative tale of the Monkey King, Sun Wu-kong, who created clones of himself from his own hair in the classic novel set in the Ming dynasty, *Journey to the West*, which inspired cloning of Dolly the sheep during the 20th century (Campbell, Mcwhir, Ritchie, & Wilmut, 1996). The cloak of invisibility in the Harry Potter series may become a reality with the metamaterials currently being investigated by American and British scientists (Pendry, Schurig, & Smith, 2006). Therefore, when human beings encounter the unknown, the exercise of imagination can generate many advances. Exploration, testing, and problem solving can yield many unexpected achievements that change the world (Mey, 2006; Osborn, 1953; Zabriskie, 2004; Zhao, Hoeffler, & Dahl, 2009).

Imagination is an innate ability of human beings, the basis for all creative activities, and the result of cognitive and emotional processes. Imagination operates based on daily life experiences that inspire creative activities (Lindqvist, 2003; Vygotsky, 1930/2004). Economic and cultural changes must be mediated by imagination and creativity, whereas scientific education is a good way to cultivate talented individuals with rich imaginations and creativity (McCormack, 2010). In other words, imagination constantly affects our thinking, language, and experiences (Adams, 2004; Grant, 2004; Mountain, 2007). The integration of imagination into scientific education and the use of different topics, such as the process of invention, is the key element to facilitate students to create products with their imagination. It can also provide opportunities for them to explore and stimulate their learning in order to find the best solutions to problems. These promote their ability to live well in the future (Church, 2006).

However, the definition of imagination is broad and vague. Gerard (1946) considered imagination to be an activity that produces novel concepts or mental insights. Lothane (2007) claimed that imagination is a basic ability to form mental images and link aspects of reality through visual images. Osborn (1953) has divided imagination into two categories, meaningful and non-meaningful. Meaningful imagination includes visual imagery such as speculative imagery, reproductive imagination, and structural visualisation, in addition to vicarious imagination such as empathy and role play. Non-meaningful imagination includes hallucinations, illusions, and dreams. Pelaprat and Cole (2011) characterised imagination as a process of image making that eliminates “gaps” arising from biological and cultural–historical constraints and that enables ongoing coordination of thoughts and actions. Innovation and creativity originate from rich imagination, whereas imagination is the precursor of the imagination process. Therefore, in the domain of scientific innovation, imagination is the mental activity that links daily life experiences and generates novel ideas. This mental activity is not limited by rules, nor is it hindered by current modes of thinking. It is an ability to construct images in the brain that are further concretised and visualised to generate ideas or prototypes that can solve current problems in life.

1.2. Factors affecting imagination

Osborn (1953) believed that people with more active imaginations and broader knowledge bases also have stronger associative abilities. Associative ability has an important status among the accidental factors contributing to creativity. As proposed by Lothane (2007), imagination is a basic ability that forms mental imagery or links events with ideas through the visualisation of images; thus, associative ability is a key element in imagination. Furthermore, imaginative people also need to have a capacity for sharp observation. Both of observation and imagination are abilities essential for conducting scientific research (De Cruz & De Smedt, 2010). Only by having the ability to constantly observe surrounding events or objects can one perceive an invariant truth or unique phenomenon. Imagination needs to be based on observation to enable us to deduce new ideas from what has been learned (Chen, 2000; Zeng, 2009).

Additionally, factors in the external environmental, such as multi-sensory stimulation, an atmosphere of openness, abundant resources, and teacher incentive awards, are major influences on imagination (Gallas, 2001; Osborn, 1953; Wood & Endres, 2004; Zabriskie, 2004; Zarnowski, 2009). Long, Winograd, and Bridge (1989) described seven perceptual forms of imagination: visual, auditory, gustatory, olfactory, tactile, kinaesthetic, and organisation sense. Douville (2004) also believed that the Sensory Activation Model (SAM), which relies on multi-sensory stimulation, is helpful for stimulating students’ imaginations. Studies have shown that students in multi-sensory imagination groups have greater imagination ability than do those in other groups (Wood & Endres, 2004). This shows that imagination is closely linked to the concrete perceptual experiences available in an individual’s current environment (Reijnders, 2010). Through multi-sensory stimulation, students can be facilitated to develop their imaginations and form more ideas through free association. At the teaching site, an open learning atmosphere that encourages and emphasises innovation facilitates the development of imagination and the ability to engage in creative expression. Teachers play a key role in establishing the atmosphere of the teaching site. Establishment of an open and free creative space by teachers will provide an environment that will not threaten the students but will encourage their imaginations. This type of atmosphere will help students generate notions that are not limited by current thinking modes (Dilek, 2009) and promote a continuous flow of creative ideas.

1.3. Purposes of the study

Through the operational process of imagination, students develop new and creative ideas that can lead to the generation of products or concrete objects (Eckhoff & Urbach, 2008). This process provides students with opportunities to explore the world, identify their interests, find solutions to problems, and further develop abilities that are necessary for the future

(Church, 2006). Based on these assumptions, we used qualitative interviews and classroom observations to systematically collect, record, and analyse data related to the Scientific Imagination Processes underlying the development of entries to the International Exhibition for Young Inventors (IEYI) submitted by the students of award-winning teachers and to identify the factors that influence this process in students.

2. Method

2.1. Participants

IEYI award-winning teachers were recruited from Kaohsiung, a city in southern Taiwan, as research participants. Sample selection was guided by considerations of representativeness and voluntary participation.

Participants were divided into two groups. The first group included five IEYI award-winning teachers from various elementary schools in Kaohsiung. Teacher S (a male with 34 years of seniority and a master's degree in education) is a homeroom teacher for the higher grades in an elementary school who had been instructing students participating in IEYI competitions for six years (2004–2009) and who had supervised 16 projects. Teacher C (a male with 22 years of seniority and a master's degree in education) is a natural science teacher for the higher grades in an elementary school who had been instructing students participating in IEYI competitions for seven years (2004–2010) and had supervised 43 projects. Teacher Y (a female with 21 years of seniority and a master's degree from National Normal University) is a homeroom teacher for gifted students in the middle grades who had been instructing students participating in IEYI competitions for six years (2005–2010) and had supervised 86 projects. Teacher Z (a female with 26 years of seniority and a bachelor's degree from National Normal University) is a natural science teacher for the higher grades in an elementary school who had been instructing students participating in IEYI competitions for four years (2007–2010) and had supervised seven projects. Teacher W (a male with 20 years of seniority and a master's degree in education) is a natural science teacher for the higher grades in an elementary school who had been instructing students participating in IEYI competitions five years (2006–2010) and had supervised 29 projects. The average seniority of these five teachers was 24.6 years. All five are award-winning teachers with a wealth of experience in instructing students participating in IEYI competitions. For example, at the seventh IEYI 2010, which involved competition among 200 projects from around the world, the Taiwanese team was awarded one platinum, seven gold, nine silver, and 10 bronze medals, as well as 14 special awards in competition. Students instructed by these five teachers were awarded one platinum, three gold, and one silver medals (http://www.ieyiun.org).

The second group included the students who had ever been instructed by the five award-winning teachers. In total, five sub-groups of students were included: G1, G2, G3, G4, and G5. Among the five groups of students, G1 (three female students in the third grade of elementary school) and G2 (three male students in the sixth grade of elementary school) were instructed by teacher C. G3 (two female students in the sixth grade of elementary school) included students co-instructed by teachers Z and W. G4 (one male student in the fourth grade of elementary school) and G5 (one female student in the fourth grade of elementary school) were instructed by teacher Y.

2.2. Procedure

This study explored the development of Scientific Imagination Process by examining teachers' perspectives on how they prepared students for the IEYI. The IEYI starts its preliminary competition around June, and the semi-final occurs around August every year. Therefore, to accurately depict the process in which these award-winning teachers provided instruction, the data were collected over one full semester, starting with the semester beginning in March of 2010, based on a schedule arranged with each teacher.

Data were collected via interviews and classroom observations. The interviewees included the five award-winning teachers and the five groups of students instructed by them. Semi-structured questionnaires were used to interview the five teachers, and all of them signed informed consent forms before the interviews. Each teacher was interviewed three times for at least 90 min per interview. The teacher interviews focussed on descriptions of the process by which they instructed students for the IEYI as well as on the teachers' life experiences, teaching methods, modes of instruction, and other factors affecting their teaching. The outline of the first teacher interview is presented in Table 1. The second and third interviews clarified unclear wording or content from the prior interviews and explored the instructional process underpinning previous award-winning projects as well as the current status of students' education in this domain.

The interview content was explained in detail in advance to the student interviewees, who were also informed that the interviews would be audio recorded; interviews were conducted after students agreed to participate. Each group of students was interviewed once for 60 min. The interview focussed on how students generate ideas, factors affecting idea generation, and how teachers guide students toward innovative ideas. The outline for the student interview is presented in Table 1. The classes chosen for classroom observation were instructed by the award-winning teachers. The focus of the observation was teacher–student interactions during instruction related to the IEYI. We spent a total of 13 h performing classroom observations, which were arranged in coordination with these teachers' schedules and teaching methods.

Audio and video recordings were made during the interviews and classroom observations with the participants' agreement. All relevant documents, copies of projects, and photographs were subjected to further analysis. The major source

Table 1
Outlines of the first teacher interview and the student interviews.

Outlines	Participants	
	Teacher interview	Student interview
1	Describe your personal characteristics and teaching philosophies.	Describe your personal characteristics and reasons for participating in the IEYI competition.
2	Do you have past experiences relating to inventing? Where did your ideas come from?	Where do the ideas come from? What are your inspirations?
3	When did you start to instruct students for the IEYI? Why did you take on this task?	What kinds of difficulties did you encounter during the process? How did you overcome these difficulties?
4	What methods do you use to prepare students for participation in the IEYI? What are students' responses?	Who did you receive help from during the process? What kind of help? For example, teachers, parents, peers, or the utilisation of other resources.
5	How are ideas for the IEYI presented when you or your students think of them? Do you visualise the final products?	Are there any differences between the final products and the original ideas? Why?

of data was teacher interviews, which were analysed to construct the model of the Scientific Imagination Process. Data collected via student interviews and classroom observations were used to supplement these results and increase validity.

2.3. Data analysis

In this study, data analysis proceeded in four steps: data arrangement, data classification, category formation, and member check. The two major data resources used in the data-arrangement step were the interviews and classroom observations. The audiotapes of teacher and student interviews and the videotapes of the classroom observations were transcribed verbatim. Additionally, teacher–student interactions were recorded on recording tables developed by members of the research team specifically for classroom observations. Subsequently, our research team received 60 min of training about how to use ATLAS.ti software to code interview data. Five codes were used to organise the data. The first code represented the categorical identity of the participant (T: teacher, S: student). The second code represented the personal of identity the participant (each teacher and each group of students had a unique code). The third code represented the data source (I: interview, O: observation). The fourth code indicated which interview or observation was the source of the data. The fifth code was the sequence code (i.e., the placement of the particular paragraph in the whole document). The fifth code was used for only interview data (i.e., records of observations did not include a fifth code). For example, T-A-I-1-18 refers to the eighteenth coded piece of data taken from the first interview with teacher A.

The major categories were conducted based on both literature review and observations from our research team. Members of the research team members placed similar responses into the same category. A peer review revealed an agreement of .7 for this classification method (Miles & Huberman, 1994).

2.4. Validity

Given that this study adopted a qualitative approach to data analysis, we focussed on eradicating threats to validity to ensure the quality of the research (Maxwell, 1996). Longer visits to the research sites and continuous observation during the research period were used to increase the validity of our data (Johnson, 1997). We spent nine months (from March to November of 2010) studying how these IEYI award-winning teachers instructed their students. We coordinated with each teacher to collect data, conduct classroom observations, analyse teaching strategies, and identify the stages of instruction. By so doing typical responses and thinking modes were able to be identified, while the credibility of our research was also reinforced.

Experienced IEYI award-winning teachers were chosen as participants based on considerations of representativeness (Miles & Huberman, 1994; Stenbacka, 2001) and voluntary participation (Stenbacka, 2001). Data were collected through interviews and classroom observation after obtaining participants' agreement and signed informed consent.

Interview and observational data were collected in the form of thick descriptions (Maxwell, 1996; Stenbacka, 2001) to represent the actual conditions in a detailed and complete manner. These descriptions included participants' personal backgrounds, teaching processes, and tones of voice and emotions during interviews with clear and detailed descriptions provided dynamic depictions of participants. Additionally, a member check (Maxwell, 1996) was also conducted. This procedure, also known as respondent validation (Johnson, 1997), refers to the process by which we discussed their interpretations of the previous interviews with participants at the beginning to clarify any uncertainties in order to continue the subsequent interviews. The credibility of the data was thus confirmed through the feedback of research participants.

In terms of data analysis and presentation, triangulation (Denzin, 1978) is the method most commonly used in qualitative research to reduce threats to validity. In this study, triangulation was performed by using multiple data sources; these included verbatim transcripts of interactions, recording tables for classroom observations and student projects, interviews, observations, discussions among panels of experts, and routine meetings of the research team to discuss procedures. Therefore, the results of the analyses were presented in both qualitative and quantitative forms (Miles & Huberman, 1994).

3. Results and discussions

3.1. Model of the Scientific Imagination Process

Fig. 1 illustrates the process of scientific imagination and how students used their imagination to create meaningful innovations under the guidance of their teachers. An original set of ideas for solving problems was initially generated, and several that best fit the specific purpose were culled from this set. Students searched for, clarified, associated, and reassembled the relationships among ideas and subsequently integrated them. Through considerations of practicality, a concise idea capable of solving problems was formulated. Through data collection, deduction, and analysis, we found that the Scientific Imagination Process had specific characteristics during each stage, and that the process was dynamic and cyclical. This process could be divided into Initiation Stage, Dynamic Adjustment Stage, and Virtual Implementation Stage. Different core components were required for each stage. Specifically, the following four different components were required: (1) Brainstorming; (2) Association; (3) Transformation and Elaboration; and (4) Conceptualisation, Organisation, and Formation. The "Illuminated Shoes" idea described below, which was awarded a gold medal at the seventh IEYI in 2010, represents an example of the model of the Scientific Imagination Process and can clarify the operation of each stage.

3.1.1. Initiation Stage

The Initiation Stage was the first stage of the Scientific Imagination Process and starts with students identifying a problem and then using their inborn imagination (Osborn, 1953) to explore possible solutions to the problem. As shown in Fig. 1, the white symbols on the first-level cloud represent the ideas generated by inborn imagination ability. Most of these original ideas are irrelevant to the problem to be solved. The coloured symbols represent the ideas generated by thinking focussed on the specific problem to be solved. Thus, the core task during the Initiation Stage was generating as many ideas as possible to solve the problem. Initial Stage emphasised the quantity of ideas. The expression of one's imagination required more than just the ability to keenly observe one's surroundings. Moreover, M. Csikszentmihalyi's study (1996) indicated sufficient curiosity about how things are produced and how they work, as well as a broad range of interests, are also needed for outstanding innovators to generate ideas. An adventurous spirit is also required, for without it one can hardly identify interesting questions and elaborate on interesting thoughts. In other words, people with great imaginations start by being curious about things in their daily surroundings and then develop the desire to understand what remains unknown. When they face problems, they maintain an open attitude and have wide-ranging interests, and develop many ideas by using their imaginations to link past experiences with new knowledge and solve the problems they encounter by all means (Lindqvist, 2003; Sternberg & Williams, 1996; Ward, 1994; Zabriskie, 2004; Zarnowski, 2009; Vygotsky, 1930/2004).

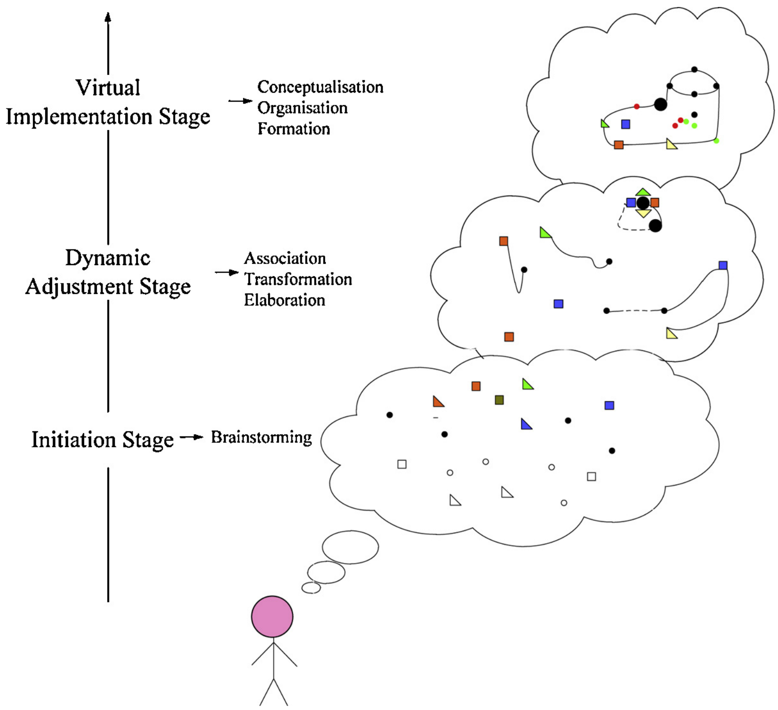

Fig. 1. Scientific Imagination Process.

During the nine months of research, we collected information about 60 projects via 15 teacher interviews, six interviews with student groups, and observations of six classroom sessions devoted to IEYI projects. The 60 projects were classified according to their characteristics. The majority of them (41%) were in the housing category; this was followed by those in the stationery category (20%), the entertainment category (10%), and the cutlery category (7%). Another classification of these projects by the sources of the ideas that generated them revealed that mostly (57%) originated from the need to solve personal problems encountered during daily life; this was followed by those generated by the need to solve other people's (including family members' and friends') problems (33%), and the remaining 10% originated in other sources. The characteristics of the projects indicated that students used their scientific imaginations to search for ideas that could solve problems. Most ideas originated from the intention to solve problems or deal with inconveniences the students encountered in their surroundings. This finding confirmed the definition of scientific imagination used in this study as it reflected the role of imagination as the mental activity that links daily life experiences with the generation of novel ideas.

It is noted that students' ideas formed in the Initiation Stage were highly similar (T-S-I-1-83, T-C-I-1-63, T-W-I-2-6) possibly because students at the same stage of learning had common life experiences. As Vygotsky (1930/2004) pointed out that an individual's life experience is the source of imagination and creativity. The process of gaining insight into one's surroundings stimulates the generation of new ideas and thus the production of innovative products. To aid in the development process of imagination, teachers used questions to guide students and help them to utilise their daily life experiences to solve problems.

> I have a series of related courses. First of all, I have to give a lot of examples to teach students that invention is possible during our lives. Invention is a way of surviving, of meeting the needs for food, clothing, housing, transportation, and recreation. For example, if an invention is needed to peel an apple, wash rice, or cook an egg, inventors will make it available to the market. Secondly, I give a lot of examples to teach students that this is the motivation for invention. In other words, we need inventions to solve problems in life, which is the origin of invention (T-Y-I-1-18).

Consideration of the use of stationery by students might clarify this point. During their education, students need to have access to pens at all times. Therefore, students focused their scientific imaginations on diversifying the functions of pens or making them more convenient to carry. For example, students generated ideas for multi-function pens and multi-function pen caps. The following exchange involving Teacher W illustrated the roles of guidance and the similarity of ideas during this stage:

> Researcher: The teachers mentioned that students tend to have common experiences. For example, how do we guide students to improve pens?
> Teacher W: I would guide them through the additional functions of pens. For example, we developed a "banana pen" this year, which was not intended at the beginning. We did this because we had the need to improve the usage of pens, and this product came out at the end (T-W-I-2-14).

The process by which teachers guided students to generate ideas and the similarities among these ideas were explained as follows:

> Researcher: In this case, regarding pens, do many students have a similar thinking process?
> Teacher W: When this occurs, it is because the process takes place in the class, which contains a pyramid-like structure of students. Students at the top of the pyramid have different background knowledge and experience. They are like the sparks in a campfire. Their ideas spread among their classmates, and influence them . . . The thinking in the class is fast because students have a common culture and way of communicating. It is easy for them to understand one another. Therefore, some of them come up with great ideas, so the next thing that needs to be done is to pin all these ideas down. First of all, we pick out the best three for discussion. The other students have questions about these ideas (i.e., about how to make the pen easier to operate and perform more functions). Every student has some unique thoughts, which should be shared (T-W-I-2-16).

During Initiation Stage, teachers adopted the principle that "good ideas come from many ideas" (T-Y-I-1-21, T-C-I-1-42) and provided students with stimulation and models from their own life experiences. The teachers guided and encouraged students to "initiate ideas without boundaries, and to think of anything even if it is impractical" (T-Y-I-1-74) and to "imagine without limitation", adding, "it's okay no matter what ideas you come up with" (T-W-I-1-12). In other words, the guiding principle in Initiation Stage is that "thinking more" does not necessarily produce "better" ideas. However, better ideas emerge from "more ideas" (Lin, Lien, & Jen, 2005).

One common way that teachers tried to guide students involved presenting detailed descriptions of the projects completed by previous students. For example, one teacher noted, "Of course, the process of student instruction is to first let them appreciate other students' projects" (T-C-I-3-6). To increase their motivation to generate ideas, students should be allowed to think slowly and on a voluntary basis (T-Y-O-1, T-Y-O-2). In this stage, students express their ideas verbally as well as illustrate them with simple pictures or in writing.

The following other responses emerged from the interviews:

> Generally, we used pictures as a starting point, and then we gave some examples and asked the students to describe their ideas verbally. I explained to them that they can find the problems in their ideas through writing, which is

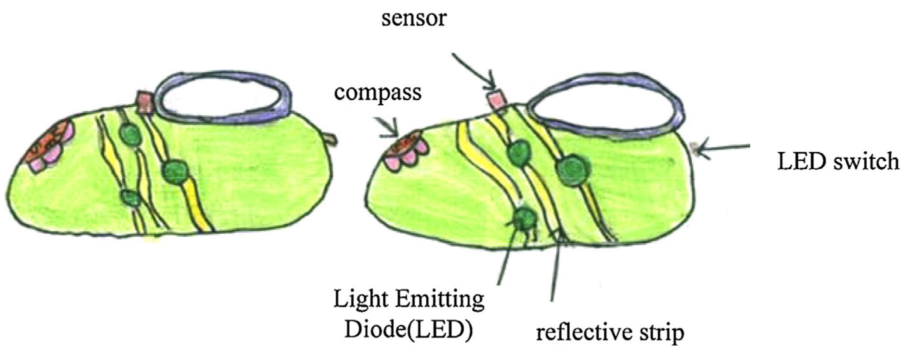

Fig. 2. Prototype of the Illuminated Shoes. The project was created by student group G1, guided by teacher C, and awarded a gold medal at the seventh IEYI in 2010.

> normally different from their thinking. After writing, I asked them to draw, during which they found more problems. Therefore, the feasibility can be repeatedly tested (T-C-I-1-14).
>
> If there were no drawings or descriptions, which would be difficult for further discussions, therefore, I would ask them to draw simple pictures without considering whether they are beautiful. Afterwards, we reminded them to add some simple descriptions of the basic structure of their ideas so that they could be more easily understood by others when they presented the ideas (T-W-I-1-24).
>
> As sometimes students' thinking differed from their talking, sowe encouraged the students to draw as well as write out their ideas to be understood better. For those who wrote about their projects, I told them to concentrate on thinking. They should write whatever they were thinking, even using phonetic symbols, and then reread their writing afterwards (T-Z-I-2-7).

The "Illuminated Shoes" project (Fig. 2), which was created by student group G1 (three girls, coded as CS1, CS2, CS3) under the guidance of teacher C, is an example of this process. When teacher C instructed group G1 to identify unsolved problems encountered in daily life through group discussion, students agreed that finding a source of light in the dark was a common issue. Indeed, walking in the dark without a flashlight was inconvenient. The following examples were provided by Teacher C to illustrate this point of view:

> I had experiences of going back to my home and shopping in the countryside. There are no streetlamps at night, and I have no hand free to use a flashlight because I have to carry many things in my hands (S-I-CS3-1-11).
>
> I went camping with my family, and we went to a big park to see lightning bugs. We had to walk down many stairs to the park, but there was no streetlamp on the road. We didn't have a flashlight and really were afraid of falling down (S-I-CS1-1-12).

This inconvenience experience of walking in the dark motivated the student to invent something to solve the lighting problem. In other words, this situation presented a "problem to be solved". After discussions under teacher's guidance, the initial solutions involved carrying a flashlight, candles, or glow sticks. The students recorded these ideas either in writing or drawings for future discussion with their teachers or classmates.

Thus, the focus of Initiation Stage was on how many ideas the students could generate to solve the problem. During Initiation Stage, the key task involved using one's imagination to generate ideas to solve problems encountered by the students themselves or by others in daily life, which in this study we have named it as *man-hsiang* (漫想) in Chinese. This is also known as Brainstorming which refers to the process of abundant ideas generation. Brainstorming is a free and limitless kind of thinking that is transformed into problem–solution-oriented thinking (T-Y-I-1-28, T-Z-I-1-17, T-S-I-1-50, T-W-I-1-16). Through Brainstorming, students could break through limitations and come up with many ideas to solve problems.

3.1.2. Dynamic Adjustment Stage

As shown In Fig. 1, the second-level cloud represents the changes made to ideas during the Dynamic Adjustment Stage, and the lines linking ideas represent the relationships between ideas. The line indicates a stronger link between ideas. The dotted line between ideas indicates a vague relationship between them. By grasping the relationships among ideas, students formulate new ideas for solving problems.

Teachers played a key role in guiding students during the Dynamic Adjustment Stage. Teachers raised questions such as "Can these ideas solve problems in daily life?" (T-Y-I-1-17, T-Z-I-1-22, T-C-I-3-17) and "Are these ideas novel?" (T-C-I-1-18, T-C-I-2-15, T-W-I-1-21, T-S-I-2-73) to guide students as they reflected on and adjusted their ideas. In this stage, both parental support and peer interactions could influence a student's ability to engage in associative and novel thinking. Parental support included providing resources (i.e., financial and knowledge-based support) to help students with their inventions (T-I-C-2-61). The interactions among classmates were helpful for communicating life experiences, which could also contribute possible solutions.

> They normally use team discussions. I prefer various opinions, which bring out different ideas. Younger students are good at imagination. As every individual has a different idea, the more of them the better. I use many approaches to encourage them to talk (T-I-Z-1-50).

During this process, the focus was not limited to helping students generate ideas that could be turned into finished products. Rather, the objective was to guide students away from their abstract and impractical ideas by drawing on the teachers' experiences and professional knowledge and to direct attention towards notions that were more likely to solve problems (S-G5-I-1-20). During the teaching process, teachers should encourage students to engage in discussions with teachers, peers, and parents (T-Y-O-1, T-W-O-1) to the end of reaching a consensus about which of the ideas were novel and practical. The participants noted the following in this regard:

> Taking your time to think enables you to form many combinations. The outcomes remain open (T-S-I-3-1).
> Sometimes we may also provide ideas that are not fully feasible. We can discuss several ideas until a feasible one occurs. We can also choose one idea to develop further (T-C-I-1-13).
> However, communication among classmates is quick because they have a common culture and language. It is easy for them to grasp what one another is thinking. With this peer communication, though not all students may participate in the discussion, it is likely that 10–20 students may have their own opinions. Teachers can emphasise some of these opinions. For example, choose three opinions and start the first peer discussion, and other students may generate some questions (T-W-I-2-17).

Thus, in the Dynamic Adjustment Stage, which occurred after the Scientific Imagination Process has been initiated, students identified relationships among ideas and repeatedly modified them to generate new ideas. There were two components of imagination operating during this stage. The first involved how to envision relationships among ideas; that is, students should link related ideas, extend the concepts behind ideas, or identify the contradictions between ideas and reorganise them accordingly (Cheng, Wang, Liu, & Chen, 2010; Koestler, 1964; Osborn, 1953; Pelaprat & Cole, 2011; Vygotsky, 1930/2004; Ward, Smith, & Vaid, 1997). We have named it as *lien-hsiang* (聯想) in Chinese in this study, which is also known as Association. The core objective of Association was in quantity. Students were supposed to find as many relationships as possible among ideas.

The second component emphasised on quality, i.e. it involved conferring new meanings on an idea within an associative network to transform it into a novel idea. We have named it as *chi-hsiang* (奇想) in Chinese in this study, which is also known as Transformation and Elaboration.

Take "Illuminated Shoes Project" for example. Students' initial ideas were using flashlights, candles, and glow sticks to be actual lighting. However, these forms of lighting equipment required extra hand to carry and were likely to be forgotten. Therefore, they started thinking about "What objects are easy to carry and do not involve bringing anything extra, and can also serve as light sources?" (S-I-G1-1-13). After discussions with family members and teacher C, the students decided to create a pair of Illuminated Shoes (S-I-G1-1-8). This pair of shoes could glow as needed, could provide directions, and has an alarm function for protection. These adjustments took place as part of the Dynamic Adjustment Stage.

3.1.3. Virtual Implementation Stage

In Fig. 1, the third-level cloud represents the Virtual Implementation Stage of the Scientific Imagination Process. The focus of this stage is on implementing the idea emerging from the Initiation and Dynamic Adjustment Stages that is mostly likely to solve problems. In other words, the emphasis is on formalising the idea by creating models or prototypes (see Fig. 2).

In this stage, teachers guided the students by asking questions such as "What type of material do you want to use?" "How do you assemble this project?" and "What will the final product look like?" Teachers guided the students to discern usable clues from their daily lives by asking them questions. Teachers also help students link past experiences to explain the function of the ideas in concrete terms, and assist them in drawing designs and creating models.

Continuing the example of the Illuminated Shoes Project, student group G1 began to discuss and designed the appearance of this pair of multi-function shoes, including the parts to serve each function and how to assemble the parts. Students created a preliminary design of the appearance of the shoe after deciding to choose Illuminated Shoes as the main theme. With teacher C's assistance, student group G1 modified the design after considering the actual materials to be used. These modifications included changes to the following: LED light placement (whether it should be placed at the front or back of the shoes), the circuit diagram of the power supply, the placement and shape of reflective stickers, and the location of the compass. The students imagined what functions of the shoes should be made available and finalised their design. The prototype of the Illuminated Shoes was made after reassembling the actual material under Teacher C's guidance (see Fig. 2). These steps all took place as part of the Virtual Implementation Stage. Teacher C offered the following descriptions of this stage:

> Sometimes the ideas in our minds are perfect and simple. However, an idea can be very different when it is drawn. The students may encounter problems during the drawing stage, such as conflicts about the placements of parts. For

example, the flashlight that I just mentioned, we found that it was not easy to assemble when we started to make the flashlight. The difficulty in assembling could have come from the fact that a segment of the flashlight was movable or a part was not easy to fix in place. We eventually placed the flashlight in the front (T-C-I-3-4).

And then we made it light reflecting. Light reflection is common, as we can see in many of shoes. In addition to that is the LED light, which should ideally be placed in the back of the heels for safety in traffic. The second function is the flashlight. One of the students came up with the idea of a compass, and we placed this at the front of the shoes. The last function is an extension of the original idea and emerged during the discussion: the alarm, which beeps in emergency situations if a button is pressed. The alarm is placed in the heels of the shoes and can be operated with a switch (T-C-I-3-5).

Thus, the Virtual Implementation Stage focused on refining particular ideas and honing students' problem-solving abilities by having them draw design diagrams and models under the teachers' instruction (S-G3-I-1-6). A prototype was produced during Virtual Implementation Stage. We have named it as *miao-hsiang* (妙想) in Chinese in this study, which is known as conceptualisation, organisation, and formation. The key component refers to students can formulate a prototype to be realised in the future. The focus is on quality, i.e. how to choose the right material, how to assemble into a prototype, how to have it fulfil the expected functions, drawing the design diagram, and finalising the diagram (see Fig. 2). These abilities can be used as the basis for the development of mental imagination and the practical transformation of creative ideas (LeBoutillier & Marks, 2003; Ren, Li, Zhang, & Wang, 2012).

4. Conclusion and further research

4.1. Conclusion

This study viewed scientific imagination as the precursor of creativity. As Policastro and Gardner (1999) proposed, imagination is an ability that links previous experiences in a unique way to generate thoughts with new meanings and to produce potentially creative thinking.

Imagination encourages the development of scientific inventions (De Cruz & De Smedt, 2010). To investigate the process by which the imagination process underlying scientific invention operate, we collected and analysed data from five award-winning teachers and the five groups of students they instructed for the IEYI via teacher interviews, student interviews, and classroom observations. The results showed that the origin of scientific imagination is the desire to deal with inconveniences encountered in daily life and that problem-solving depends on the operation of imagination. This process was consistent with the findings of De Cruz and De Smedt (2010) that scientific creation and imagination process in small incremental steps rather than revolutionary leaps. Therefore, we classified the process of scientific imagination into three stages: Initiation, Dynamic Adjustment, and Virtual Implementation Stages. Different key components operated during each stage; these include Brainstorming (*man-hsiang*, 漫想); Association (*lien-hsiang*, 聯想); Transformation and Elaboration (*chi-hsiang*, 奇想); and Conceptualisation, Organisation, and Formation (*miao-hsiang*, 妙想). The operations occurring during these three stages were based on life experiences, and ideas were separated and re-assembled through dynamic adjustments that are continuously made to solve problems. Through such dynamic adjustments, ideas corresponding to real-life issues were generated on a continuous basis and refined to generate prototypes or models to be used as references for the production of actual objects in the future.

Note that the variables influencing the three stages of the Scientific Imagination Process could be classified into internal and external factors. Internal factors referred to a student's personal characteristics, whereas external factors included teacher guidance, family support, and peer interactions. Among these three external factors, teacher guidance played a key role in influencing scientific imagination. Our analysis of interviews with award-winning teachers revealed that talented students in imagination with specific characteristics, such as being free-thinking (T-Y-I-1-32, T-S-I-2-57, T-W-I-1-50), observant (T-Y-I-1-24, T-C-I-2-19), curious (T-Z-I-2-17, T-C-I-2-5), or active (T-C-I-2-3, T-Y-I-1-30) and those who enjoy challenges and behave in a relatively uninhibited way (T-W-I-1-36, T-Y-I-2-32). They were better at generating ideas, extending concepts, participating in teacher–student interactions and peer discussions, and generating truly marvellous ideas.

Although imagination is common to everyone, there are individual differences in how individuals use imagination to generate good ideas that solve problems. In this regard, our findings were consistent with those of previous research that showed that characteristics such as the ability to form new associations, the tendency to keenly observe, curiosity, a desire to learn, an open-minded attitude, an adventurous spirit, a history of multiple experiences, and wide-ranging personal interests can influence the development of imagination ability (Cheng & Wang, 2002; Csikszentmihalyi, 1996; Furnhama, Batey, Booth, Patel, & Lozinskaya, 2011; Osborn, 1953; Sternberg & Williams, 1996; Wood & Endres, 2004; Zabriskie, 2004; Zarnowski, 2009). In terms of external factors, imagination needs to be de-constructed and re-constructed by drawing on the rich material available in one's daily surroundings (Han, Hung, & Tsai, 2008). Examples of external factors include multi-sensory stimulation, role-playing, an open atmosphere, the availability of relevant resources, and teacher awards (Karwowski & Soszynski, 2008; Gallas, 2001; Osborn, 1953; Wood & Endres, 2004; Zabriskie, 2004; Zarnowski, 2009).

To sum up, the results of this study showed that the major contributors to scientific imagination are the family environment, teacher guidance, peer interactions, and multiple life experiences (e.g., reading novels and science fiction; going to movies, plays, performances, and seminars; and travelling). Factors that encouraged and facilitated students to use scientifically innovative imagination may include a family environment that provides a supportive atmosphere and resources (T-C-I-3-22, T-W-I-3-5, T-Y-I-2-12, T-S-I-2-72), and teachers who provide appropriate stimulation to guide students in their thinking (T-C-I-3-14, T-Y-I-3-20, T-Z-I-2-19, T-S-I-3-4, T-W-I-1-29), and the asking questions of and interacting with peers (T-W-I-1-22, T-Z-I-1-50, T-C-I-2-15).

4.2. Further research

However, this study still requires further clarification of the internal and external factors that influence the Initiation, Dynamic Adjustment, and Virtual Implementation Stages, especially the key factors that affect operation of scientific imagination in each stage. Therefore, for further research, we will invite award-winning teachers and domain field experts in specific domains to form a research group that uses concept maps to clarify the key factors affecting each stage through concept maps (Novak & Gowin, 1984).

Imagination is essential for innovation and is also the key to future competitive success. As the extant curricula and courses rarely mention how teachers should help students express their imagination (Egan & Judson, 2009), therefore, we will develop teaching assessment tools using the Scientific Imagination Process as the framework, which will be used to evaluate if teachers' behaviours and strategies are useful for promoting students' scientific imaginations. Additionally, we will also conduct research on curriculum materials development based on the characteristics of each stage of scientific imagination. We will further examine the suitability of the current model of the Scientific Imagination Process and the practicality of course materials and assessment tools through experimental teaching.

Finally, this study explored the Scientific Imagination Process from teachers' perspectives. Specifically, the model was constructed based on the professional knowledge and rich experiences of award-winning teachers, using data from student interviews and classroom observations as supplementary material. Further investigation is needed to determine whether students can really develop their scientific imaginations according to these three stages and whether they can actually generate outstanding ideas to solve problems under the guidance provided by teachers.

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