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Development of the scientific imagination model: A concept-mapping perspective

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ABSTRACT

This study aimed to follow up on the research conducted by Ho, Wang, and Cheng (2013) and to develop a model of the scientific imagination using group concept mapping. Participants included five outstanding elementary school teachers and four researchers from southern Taiwan. The framework developed by Trochim (1989) was used as the basis for the construction of concept mappings of the scientific imagination through five panel discussions among the experts. A review of the literature, qualitative interviews, classroom observation, and document analyses were performed on group concept mapping, and independent relevant documents were used for data validation. A qualitative method was employed for data analysis. Finally, we developed the personality, developmental process, picture-in-mind, and surroundings (3PS) model of scientific imagination. Research results indicated that the scientific imagination model not only enhanced understanding of scientific imagination but also applied to daily experiences. The results of the present study are relevant to future projects and research in this domain, including the development of academic-based checklists to foster scientific imagination, the establishment of appropriate assessment tools, and the formulation of a specific curriculum for teaching the concept of scientific imagination.

1. Introduction

Creation and invention originate from a rich imagination. Many inventions originated primarily from ideational processes within what is commonly referred to as the human imagination. Through the operational processes, manipulations, and interactions involving imagination, a human being recognises internally generated creative ideas that lead to the invention and design of concrete objects that are eventually manufactured into products (Eckhoff & Urbach, 2008). Processes stemming from the human imagination potentially provide people with opportunities to explore the world, follow their interests, find answers to problems, and further develop capabilities that are necessary for future survival (Church, 2006). In other words, imagination has a substantial influence on human thinking, language, and life experience (Adams, 2004; Grant, 2004; Mountain, 2007).

Previous studies (Dílek, 2009; Eckhoff & Urbach, 2008; LeBoutillier & Marks, 2003; Lothane, 2007; Vygotsky, 1930/2004) have shown that the definition of imagination and the factors that contribute to its operation have not been examined comprehensively enough to allow for an adequate construction of a complete model of imagination and its stages. Based on

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this reasoning, Ho, Wang, and Cheng (2013) proposed that the scientific imagination emphasises purposeful processes and defined the scientific imagination as the mental activity involved in creating new ideas that are consistent with scientific principles and are linked to daily life experiences. This mental activity is not limited by rules or hindered by current modes of thought. It is the ability to construct images in the brain, generate ideas, and concretise these mental processes in the invention or creation of objects and products. Additionally, imagination may help people to push the boundaries of current knowledge, to exceed the limitations of generally accepted definitions of reality, and to enter an expanded scientific world and develop more elaborated scientific theories, thereby leading to technological advancements (e.g., new products) that surpass the inventions of the current generation.

Furthermore, Ho et al. (2013) explored the scientific imagination by studying award-winning teachers and students in the International Exhibition for Young Inventors (IEYI) competition using qualitative research methods including interviews, videotapes, and observations. They systematically collected, recorded, and analysed the results to determine how these successful teachers instructed their students. As a result, they proposed three stages in the process of scientific imagination, namely, initiation, dynamic adjustment, and virtual implementation; they also specified four components underlying the scientific imagination, namely brainstorming, association, transformation/elaboration, and conceptualisation/organisation/formation. Their findings constituted preliminary data that clarified the definition, operational processes, and factors contributing to scientific imagination.

In this study, we attempted to use a different approach, concept mapping, to confirm the process underlying scientific imagination. The use of concept mapping can help us think about and differentiate relationships among different concepts. It organises these concepts and integrates them in a systematic, hierarchical, and structured way through symbolic representation (Chiou, 2008; Ruiz-Primo & Shavelson, 1996). Additionally, further construction of a complete scientific imagination model can be achieved by understanding the processes underlying scientific imagination and the factors that contribute to such processes. This theoretical basis should be helpful as a reference and framework for modelling the skilled teaching of a curriculum on scientific imagination. Therefore, the current study aimed to comprehensively understand the three stages and four components involved in scientific imagination (Ho et al., 2013) by constructing concept maps and to develop a model of the scientific imagination.

1.1. The scientific imagination process

The process underlying scientific imagination was constructed from a teacher's perspective based on the professional knowledge and rich experiences of award-winning teachers, using data from student interviews and classroom observations as supplementary material (Ho et al., 2013). That study divided this process into three stages: initiation, dynamic adjustment, and virtual implementation. Four different key components operate during each of the three stages: brainstorming (*man-hsiang*, 漫想), association (*lien-hsiang*, 聯想), transformation/elaboration (*chi-hsiang*, 奇想), and conceptualisation/organisation/formation (*miao-hsiang*, 妙想). These three stages and four different components are described below.

1.1.1. Initiation stage

The initiation stage is the first stage in the scientific imagination process. The main focus at this stage is on the number of ideas that students can generate to solve a problem. During this stage, the key component is the use of imagination to generate ideas to solve problems encountered by the students themselves or by others in daily life. This stage is known as brainstorming in English (Ho et al., 2013) and as *man-hsiang* (漫想) in Chinese; it refers to thinking in such a way as to generate numerous ideas without regard for usual boundaries or structures. During this stage, teachers usually try to motivate, provide models for, and encourage students to observe experiences in daily life. Operating under the overarching principle of "good ideas come from many ideas", the teacher provides students with stimulation and modelling based on life experiences, and this encourages them to use their extant knowledge base (Cruz & Smedt, 2010; Ward, 1994). Students subsequently generate new ideas by combining existing knowledge under the guidance of teachers. Overlapping ideas and repetition are common during the initiation process.

1.1.2. Dynamic adjustment stage

Dynamic adjustment is the second stage in the scientific imagination process. In this stage, students choose one novel idea from the many possible ideas generated and use it to solve a problem. The operation of the imagination during this stage includes two components. The first component is known as *lien-hsiang* (聯想) in Chinese and association in English (Ho et al., 2013). It involves finding ways to envision relationships among ideas; that is, students connect related ideas, extend the concepts behind ideas, and identify contradictions between ideas and reorganise them accordingly (Cheng, Wang, Liu, & Chen, 2010; Koestler, 1964; Osborn, 1953; Pelaprat & Cole, 2011; Vygotsky, 1930/2004). Students are supposed to find as many relationships among ideas as possible.

The second component involves transforming an emergent idea into a novel idea by exploring its associative network. This component is known as *chi-hsiang* (奇想) in Chinese and as transformation and elaboration in English (Ho et al., 2013). It entails interpreting the emergent idea in a new way, thus attaching new meaning to form novel ideas. In this stage, teachers commonly guide their students by raising questions to help them reflect on and modify their ideas. Examples of such questions include "Can this idea solve problems?"; "Has this idea been proposed before?"; and "Will it be better if certain functions or parts are added?" (Ho et al., 2013). This teaching approach is intended to encourage students not to limit their responses and expressed ideas to only what is practical, logical, or possible within standards of "the real world." Instead, a teacher with professional expertise guides students to consider unique and even impractical ideas to a practical problem.

1.1.3. Virtual implementation stage

The virtual implementation stage is the third stage of scientific imagination. It involves selecting from the various novel ideas generated earlier those with the greatest likelihood of solving problems. The students begin this stage with specific ideas for problem solving that were developed, with teacher guidance, during the first two stages. Now, students refine their previous activities to create a prototype for their specific ideas. This component is referred to as conceptualisation/organisation/formation in English and as *miao-hsiang* (妙想) in Chinese (Ho et al., 2013). Teachers guide students to think about issues such as the choice of material, techniques for assembling parts, and means of creating design diagrams and final drafts from the initial diagrams. The prototype can be used as the basis for scientific imagination and can be linked to subsequent creations.

It is worth noting that the prototype produced in the virtual implementation stage does not represent the final product of the scientific imagination process. Instead, we should consider this to be a mental product that stimulates the next cycle of imagination, which depends on students' individual life experiences. In the domain of scientific invention, all possible products can solve current problems only temporarily. Thus, these products are not regarded as permanent or fixed.

The operations occurring during these three stages were based on life experiences, and ideas were separated and re-assembled through continuous dynamic adjustments made in the service of solving problems. Through such dynamic adjustments, ideas corresponding to real-life issues were generated on a continuous basis and refined to create prototypes or models to be used as references for the production of actual objects in the future (Ho et al., 2013).

1.2. Purpose of the study

Therefore, the present study aimed to confirm the preliminary construal of the process of scientific imagination developed by Ho et al. (2013) and to gain an understanding of the factors that affect the scientific imagination using Trochim's (1989) framework of concept mapping. Furthermore, we attempted to develop a model of scientific imagination that might serve as a reference for the future development of courses, assessments, and evaluations.

2. Method

2.1. Participants

Participants in the study included Ho et al.'s (2013) research team and five teachers of award-winning in the International Exhibition for Young Inventors (IEYI) from southern Taiwan. The research team included one professor, two doctoral students, and one master's level graduate student, each of whom specialised in one or more fields of educational psychology, creativity, imagination, and science education. The IEYI award-winning team included five natural science elementary school teachers with masters' degrees (three males and two females). Their average teaching experience was 26.8 years (as of 2011). Teacher A (a male with 35 years of experience) was an elementary teacher who instructed students who had participated in IEYI competitions for 7 years (2004–2009, 2011) and oversaw 17 projects. Teacher B (a male with 25 years of experience) was a natural science teacher for the higher grades of elementary school who had advised students participating IEYI competitions for 8 years (2004–2011), overseeing 51 projects. Teacher C (a female with 23 years of experience) was a homeroom teacher for gifted classes in the middle grades and had advised students who participated in IEYI competitions for 7 years (2005–2011), overseeing 107 projects. Teacher D (a female with 29 years of experience) was a natural science teacher for the higher grades of elementary school and had advised students participating in IEYI competitions for 4 years (2007–2011), overseeing 10 projects. Teacher E (a male with 22 years of experience) was a natural science teacher for the higher grades of elementary school and had advised students for IEYI competitions for 6 years (2006–2011), overseeing 33 projects. All five are award-winning teachers with a wealth of experience instructing students competing in the IEYI and all have won several major awards in numerous international science competitions.

2.2. Procedure

The process of structured conceptualisation enables the use of a conceptual framework to guide research team members as they develop theories and concepts based on analyses of results of data collected from multiple sources, such as interviews and classroom observations. Therefore, after receiving consent from five IEYI award-winning teachers, we held five panel discussions between April and June of 2011. Each discussion lasted 3–5 h.

Before the first panel discussion, the research team introduced the IEYI award-winning teachers to the definitions, format, composition, and principles involved in constructing a concept map. Examples of templates of concept maps were provided to the teachers as references. Subsequently, content related to the three stages and four components of the scientific imagination process (Ho et al., 2013) was used to construct the map.

Table 1
Constructing three concept maps using Trochim's (1989) framework.

Preparation	Generation of statements	Structuring of statements	The representation of statements	The interpretation of maps	The Utilisation of interpretable conceptual framework
To choose appropriate individuals to participate in the group discussion: →Ho et al.'s (2013) researchers →Five IEYI award-winning teachers Referenced materials: →Ho et al.'s (2013) scientific imagination process →students' documents →students' creations	To propose perspectives and concepts related to each stage of the scientific imagination process. ↓ To generate concepts in response to the viewpoints and concepts proposed. ↓ To discuss whether the concepts were appropriate for each stage until they reached a consensus.	To classify concepts into hierarchies. ↓ To evaluate whether it was appropriate to put certain concepts into the same hierarchical level for the purpose of making comparisons. ↓ To place concepts that were the same or similar into one category and separate concepts that were dissimilar or had divergent characteristics into distinct categories based on affiliative or generalizing relationships. ↓ To identify the hierarchical relationships among concepts.	To link any two related concepts to construct meaningful propositions. ↓ To clarify the relationships between and meanings of two given concepts. ↓ To explain each pair of statements and illustrate an understanding of each pair of statements. ↓ To identify these between-cluster concepts and apply the appropriate labels.	To raise examples that were not selected in step one. ↓ To identify the concrete examples learned by analogy and raise by members in the concept map. ↓ To identify concepts that were in conflict with those generated by the teacher team. ↓ To promote understanding and a sense of respect for differing opinions. ↓ To yield the preliminary concept map of the three stages and four abilities.	To complete the initial concept map depicting the three stages and four abilities. ↓ To discuss teaching strategies, factors that affect scientific imagination, and the characteristics of the four abilities that teachers have used to guide students involved in IEYI competitions; ↓ Future uses: →to help students to implement scientific inventions →to develop checklists for use in teaching science and designing curricula related to the scientific imagination process.
before the discussion	the first time	the second time	the third time	the fourth time	the fifth time

---Five panel discussions from April to June of 2011--->

During the five panel discussions, we used Trochim's (1989) framework (Table 1) to outline the six steps by which projects are evaluated to yield a structured conceptualisation. The six steps are: (a) *Preparation*: choosing representatives from the team to focus on the main points of concept map development; (b) *Generation of statements*: stating viewpoints and concepts that emerge through brainstorming; (c) *Structuring statements*: classifying concepts by hierarchies and identifying affiliative, generalising, and hierarchical relationships among concepts; (d) *Representing statements*: explaining the meanings of concepts and the relationships among them; (e) *Interpreting maps:* leading group discussions to clarify concepts that are inaccurate or contradictory based on those from the teachers' team that preceded the expert panel; and (f) *Utilising an interpretable conceptual framework*: specifying the teaching strategies used, the factors that affect scientific imagination, and the information generated by application of the four abilities.

The panel discussions were audio-recorded with the participants' consent. Related documents, copies of projects, and photographs were subjected to further analyses. Of these materials, the main data source was the discussion among experts. The other data were analysed as ancillary information to reduce threats to the validity of our model of the scientific imagination.

2.3. Data analysis

The five panel discussions were transcribed verbatim by members of the research team. Each transcript was identified with two codes: one identified the panel within the sequence, and the other noted the date on which the panel was held. For example, in the code "3_20110427", "3" represents the third meeting, and "20110427" represents April 27, 2011. Additionally, A, B, C, D, and E represent the five elementary school teachers, S represents the student who joins the IEYI, and R represents the author of the study.

This study analysed detailed data on the preparation, process, and results of each of five 3–5-h panel discussions (Maxwell, 1996; Stenbacka, 2001). The in-depth and detailed descriptions of participants and their discussions should provide readers with a complete understanding of the study. Moreover, this study also involved a member check (Maxwell, 1996), which is also referred to as respondent validation (Johnson, 1997). Prior to each discussion, the research team repeatedly checked results and clarified ambiguities in previous discussions by obtaining feedback from the members of the research team to confirm the accuracy of the information.

To ensure the representativeness of the analysed results, the research team strictly followed the six steps (presented in Table 1) described in the next section in their development of the concept map until consensus was achieved in regard to the three stages and four components. The relationships among concepts were examined by repeatedly checking the main data source and repeatedly analysing the content. The concept map was developed to understand the factors affecting the scientific imagination process so as to provide additional data regarding the theoretical aspects of the scientific imagination model.

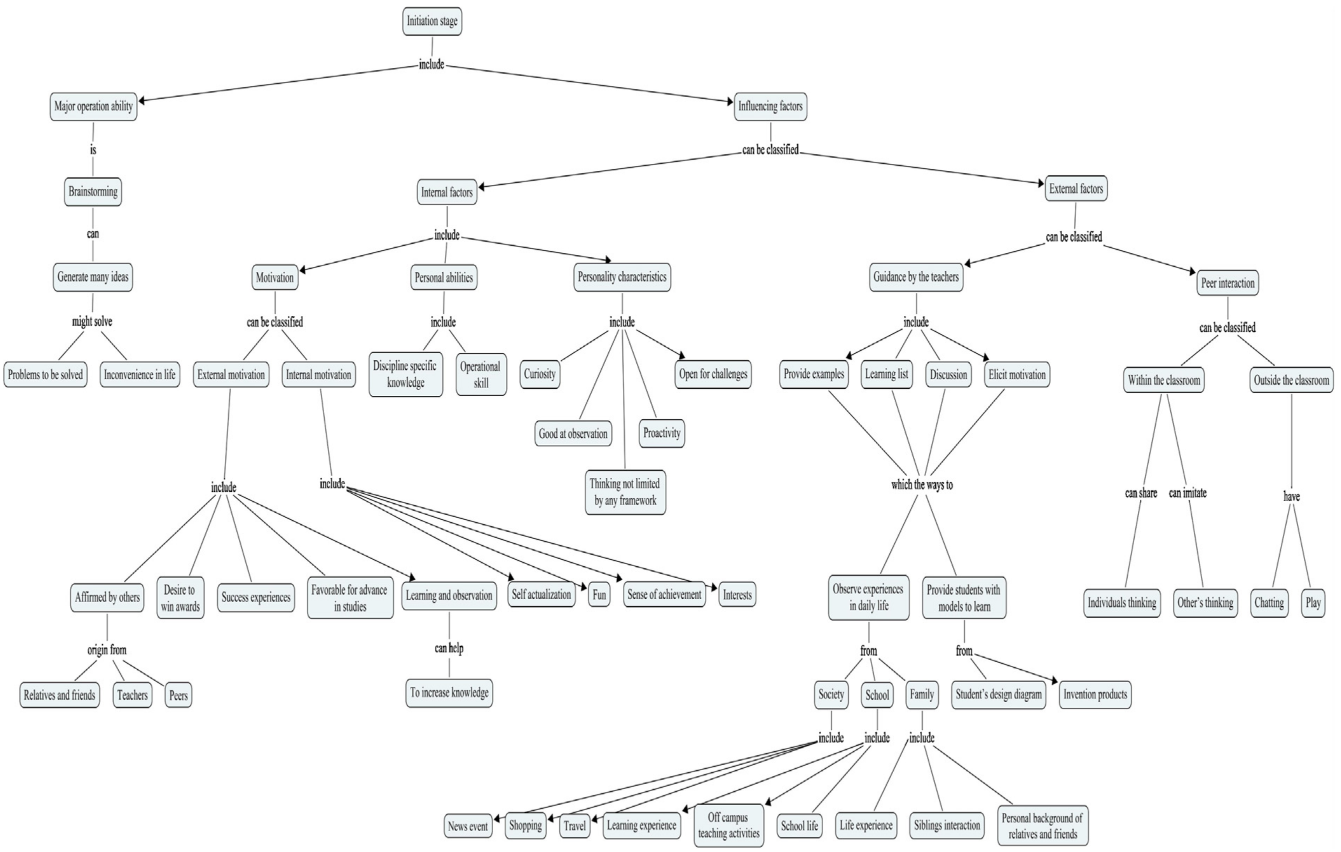

Fig. 1. Concept map for the initiation stage.

The sample used in this study complied with the standards for representativeness (Miles & Huberman, 1994; Stenbacka, 2001) and voluntary participation (Stenbacka, 2001). Panel participants included outstanding teachers as well as teams of invention researchers who had been involved in Ho et al.'s (2013) study. Data were collected through panel discussions after participants provided written informed consent.

The data were also confirmed via triangulation (Denzin, 1978). This study relied primarily on data obtained during the discussion process; these were supplemented by multiple data sources, such as transcripts of the interviews conducted for Ho et al.'s (2013) previous study, records of observations, student work, and so on. The results are presented in qualitative as well as quantitative terms (Miles & Huberman, 1994) to enable the application of the triangulation procedure.

Finally, all descriptions included in the concept mappings were analysed in terms of categories and themes (Miles & Huberman, 1994), and concepts at the first level were extracted based on these descriptions. Next, common factors were integrated according to the concepts at the first level, and so on. The major categories were defined based on both a literature review and interviews conducted by our research team. Members of the research team placed similar responses into the same category. A peer review revealed an agreement of .7 for this classification method (Miles & Huberman, 1994).

3. Results and discussion

3.1. Concept mapping of the scientific imagination process

This study used data obtained from five panel discussions to construct concept maps that included the three stages and four components related to the scientific imagination process. The six steps outlined in Trochim's (1989) framework were followed to construct the concept maps. Moreover, qualitative data from previously conducted teacher–student interviews, classroom video recordings, and text recordings also assisted in the construction of the concept map by allowing for repeated evaluation and verification of the internal relationships among the concepts in the model.

At the beginning of the panel discussion, members were asked to consider the three stages of scientific imagination. After a brief description of the definition of the three stages, the panel members were asked to brainstorm about any issues, problems, features, and so on that seemed relevant to teaching students about these stages (Table 2). Furthermore, several concrete examples of the most basic concepts in the concept map were presented (Figs. 1–3). Use of the concept maps can contribute to teaching strategies, reference materials, and assessment tools related to students' scientific imagination. The follow three concept maps were described:

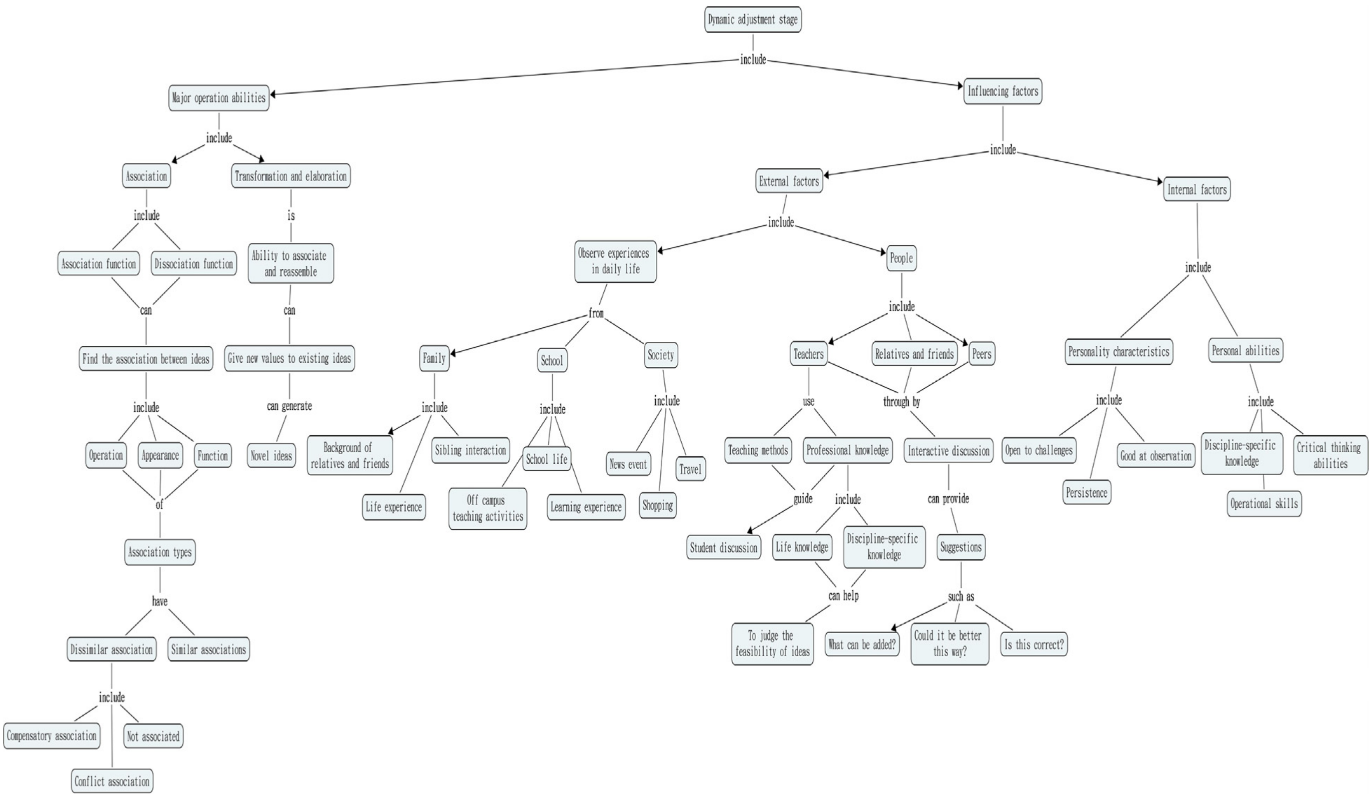

Fig. 2. Concept map for the dynamic adjustment stage.

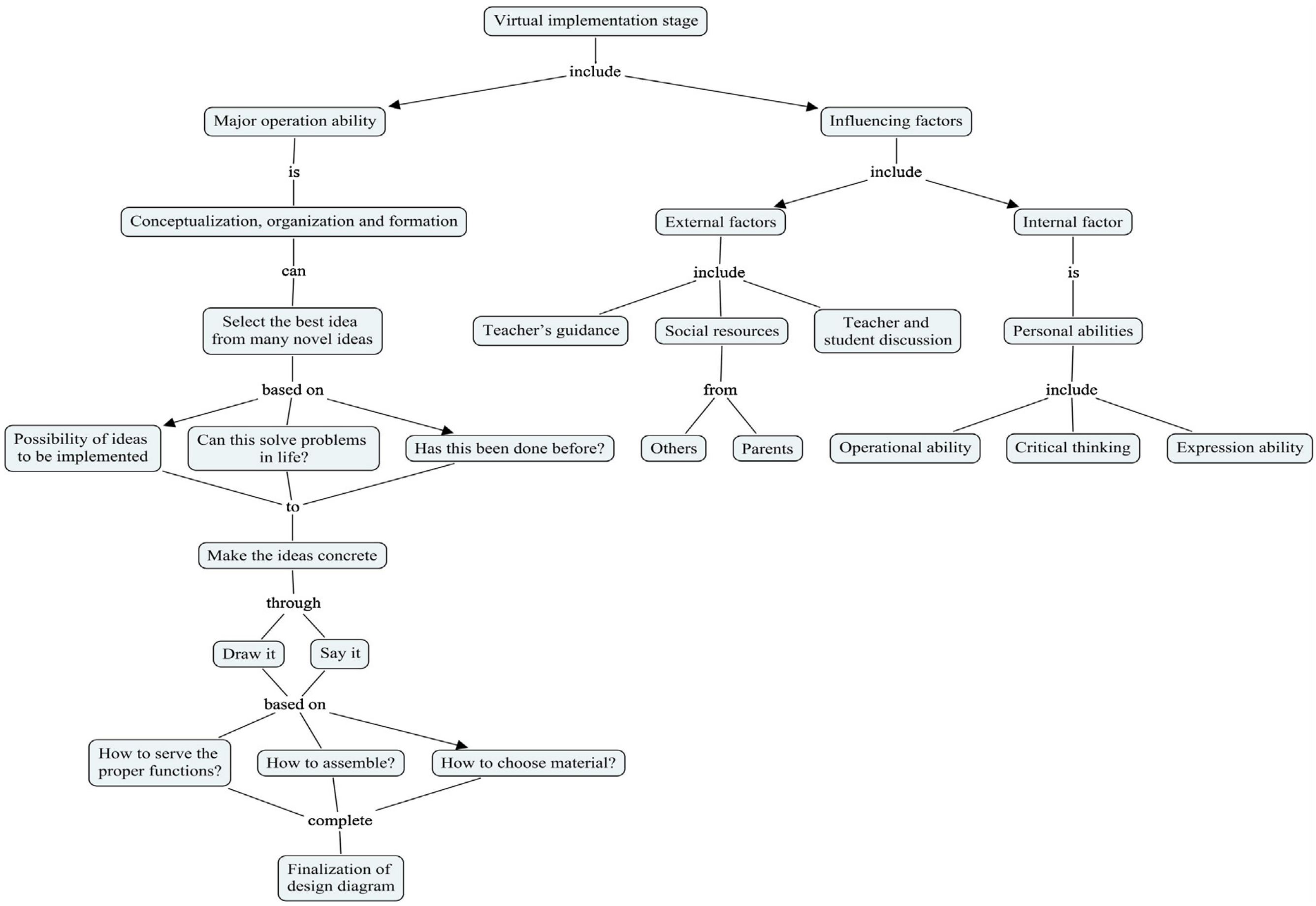

Fig. 3. Concept map for the virtual implementation stage.

Table 2
Concepts discussed in the first panel discussion.

Three stages	Issues raised by panel	Four abilities	Contents
Initiation stage	Influences: internal factors, external factors, thinking styles, personality characteristics, motivation, discipline-specific knowledge, thinking not limited by framework, curiosity, open to challenge, good at observation, active, internal motivation, external motivation, peer interaction, family environment, teacher guidance, experiences in daily life, teaching methods, teacher–student classroom discussion, learning list.	Brainstorm	Many ideas
Dynamic adjustment stage	Influences: teacher guidance, experiences in daily life, family resources, professional knowledge, teacher's view of invention, experiences from daily life, learning by modelling, guidance from non-practical to practical ideas, peer discussion, teachers' teamwork, do it yourself, mutual teaching and learning, nurturing students observation ability, not limiting student's thinking, common discussion between students and teachers.	Association	Functions of the ideas, different ideas, considered ideas, similar ideas, good ideas, impractical ideas
		Transformation/elaboration	Novel ideas
Virtual implementation stage	Influences: teacher guidance, experiences in daily life, family resources, professional knowledge, experience from daily life, peer discussion, do it yourself, mutual teaching and learning, guidance without dominating, not limiting students' thinking, common discussion between students and teachers.	Conceptualisation/organisation/formation	Concept plan

3.1.1. Initiation stage

Brainstorming was defined as the main operational ability of this stage (see Fig. 1). Ho et al. (2013) considered the definition of brainstorming to be thinking of many ideas that can contribute to addressing inconveniences or problems in living. Panel members made a distinction between internal and external factors. In terms of external factors, they distinguished issues of teacher guidance from those of peer interaction. Before participating in the IEYI, teachers explain the rules of the IEYI competition to the students and also help them with thinking and generating as many ideas as possible by using teaching strategies such as modelling, exemplifying, discussing, and using learning lists. Teachers who use modelling, for example, generally rely on previous award-winning invention products or products used in daily life. The teachers also explain the origins of the ideas behind these award-winning products, their production process, and their functions to stimulate generation of ideas about product appearance, functions, and limitations.

The panel noted that, in addition to serving as the source of pedagogical models and questions, students' external environment is an important influence on imagination (e.g., its multi-sensory stimulation, atmosphere, resources, support, and incentives and awards for teachers). This echoes the findings of a number of other authors (e.g., Gallas, 2001; Osborn, 1953; Wood & Endres, 2004; Zabriskie, 2004; Zarnowski, 2009). Of these external factors, daily life experiences are very important. Indeed, rich and diversified daily experiences can stimulate various senses. Long, Winograd and Bridge (1989) described seven perceptual forms of imagination: vision, audition, taste, olfaction, touch, kinesthesis, and organisational perception. Douville (2004) also believed that the multisensory stimulation described in the Sensory Activation Model (SAM) helps facilitate students' imagination (Wood & Endres, 2004). Thus, we know that human imagination is closely associated with simultaneous concrete sensory experiences (Reijnders, 2010). Through multisensory stimulation, students' imagination can be facilitated; through the rich and diversified materials found in life, many ideas can be generated via free association. These can be based on life experiences involving family, school, or society. Students' experiences at home, the backgrounds of their relatives and friends, and sibling interactions can all influence the type of life-related problems that students encounter. They also affect students' choice of problem-solving methods.

Additionally, given that students spend significantly more of their time at school than at home, school-based learning, general overall life events, and school-initiated off-campus educational offerings likely serve as catalysts for the ongoing development of students' imaginations. The inconveniences encountered during students' school life may result in students discovering new ideas that lead towards beneficial changes. Peer interaction, that is, the classification of peer-to-peer discussions based on whether they occur in the intra- or extra-classroom setting, is another important external factor that may influence students' ideas. Regarding peer interactions occurring in class, student-to-student sharing of ideas may stimulate the production of more ideas. In extra-classroom environments, good ideas may result from the peer-based actions of chatting or playing. Interactive sharing between peers with regard to life experiences may also facilitate the generation of many new ideas.

On the other hand, internal factors affecting the initiation stage include motivation, personal ability, and personality characteristics. Motivation can be classified as either external or internal. In this study, a small number of students elected to become involved in competition for the purpose of achieving academic advancement. Those who had won awards in prior competitive events appeared to recognise that their previous experiences of success were a vehicle towards stimulating their desire to try to win again. Other students appeared to be motivated by the possibility of gaining recognition from their peers, teachers, relatives, and friends and by acknowledgement of their success through compliments made by the significant people in their lives. Moreover, competitors have opportunities to observe other students' projects. Access to this type of student experience may foster future ideas and students' motivation to gather useful information. In terms of internal motivation, many students considered invention to be a source of great interest and fun, which enabled them to gain a sense of achievement during the invention process. Gifted students may want to challenge themselves to achieve self-actualisation.

3.1.2. Dynamic adjustment stage

This stage includes two major operational abilities: association and transformation/elaboration (see Fig. 2). The associations among ideas can be identified based on separation and linked functions, and functional, aesthetic, and operational similarities and dissimilarities can be identified. Dissimilarities include conflicts, complementary associations, and the absence of association. Identifying associations based on similarity and dissimilarity enables students to discover new associational relationships and reassemble the ideas, which reflects the use of transformation and elaboration in attaching new values to existing ideas and generating novel ideas by reorganising associations. Thus, the process of imagination is based on daily life experiences and the reciprocal interaction of association and disassociation (Eckhoff & Urbach, 2008). Osborn (1953) considered individuals with active imagination and rich knowledge to have stronger associational abilities. Association plays an important role in creativity and encourages students to think from diverse perspectives, such as those involving the shapes and foundations of objects; it also provides students with multiple stimuli for activating related nodes in the structure of their associative networks (Cheng et al., 2010). As noted by Lothane (2007), imagination is a fundamental ability to form mental images or to use visual images to generate associations among things or ideas. Therefore, association is a key condition for imagination.

Unlike the initiation stage, the dynamic adjustment stage is affected by internal factors, including individual abilities and personality characteristics. In this stage, we added critical thinking to the required personal abilities. Having generated numerous ideas, students were guided to refer to their individual store of formal knowledge, their operational skills, and other sources of data as references in questioning, debating, criticising, and discussing their ideas in terms of both the feasibility of a specific idea for problem solving and the consideration of potential modifications of selected ideas. However, data from interviews with students revealed that students' initial ideas differed from their final products (Ho et al., 2013). Teacher C indicated that many of the inventions produced by elementary school students were not very refined, and some ideas generated by them were difficult to implement. However, the ideas proposed were interpreted as being "imaginative". For example, using Finland's Hernesaari 2012 plan for rebuilding, the Helsinki city government invited six teams to submit proposals. Three plans were proposed by 100 3–17-year-old Arkki architecture students from the Hernesaari area. Story telling was used to help the 3–6-year-old children think about the atmosphere in Hernesaari, thus enabling them to participate in the design of a city of the future (Lin, 2011). Younger children also have limited operational abilities that likely influence their final products. However, their imaginations know no bounds.

External factors include characteristics such as the appreciation of people and the sense that daily life experiences are of value. Students' experiences of day-to-day life are not only a source for various ideas but also a guide for helping students to identify relationships between different ideas. Therefore, competent and valued science teachers possess a requisite set of resources, including being highly knowledgeable regarding their assigned curricula and well-practiced in a broad range of teaching abilities, with the capacity to apply versatile, flexible, and diverse teaching methods and to maintain a careful awareness of the progress and development of their students' education. Such valued teachers integrate their individual discipline-specific professional knowledge into their methodology so as to elicit students' interest in learning, using methods that prevent students from encountering major difficulties as a necessary part of the learning process (Langer, 1993). At this stage of instruction on the topic of scientific imagination, teachers use their professional knowledge and teaching methods to

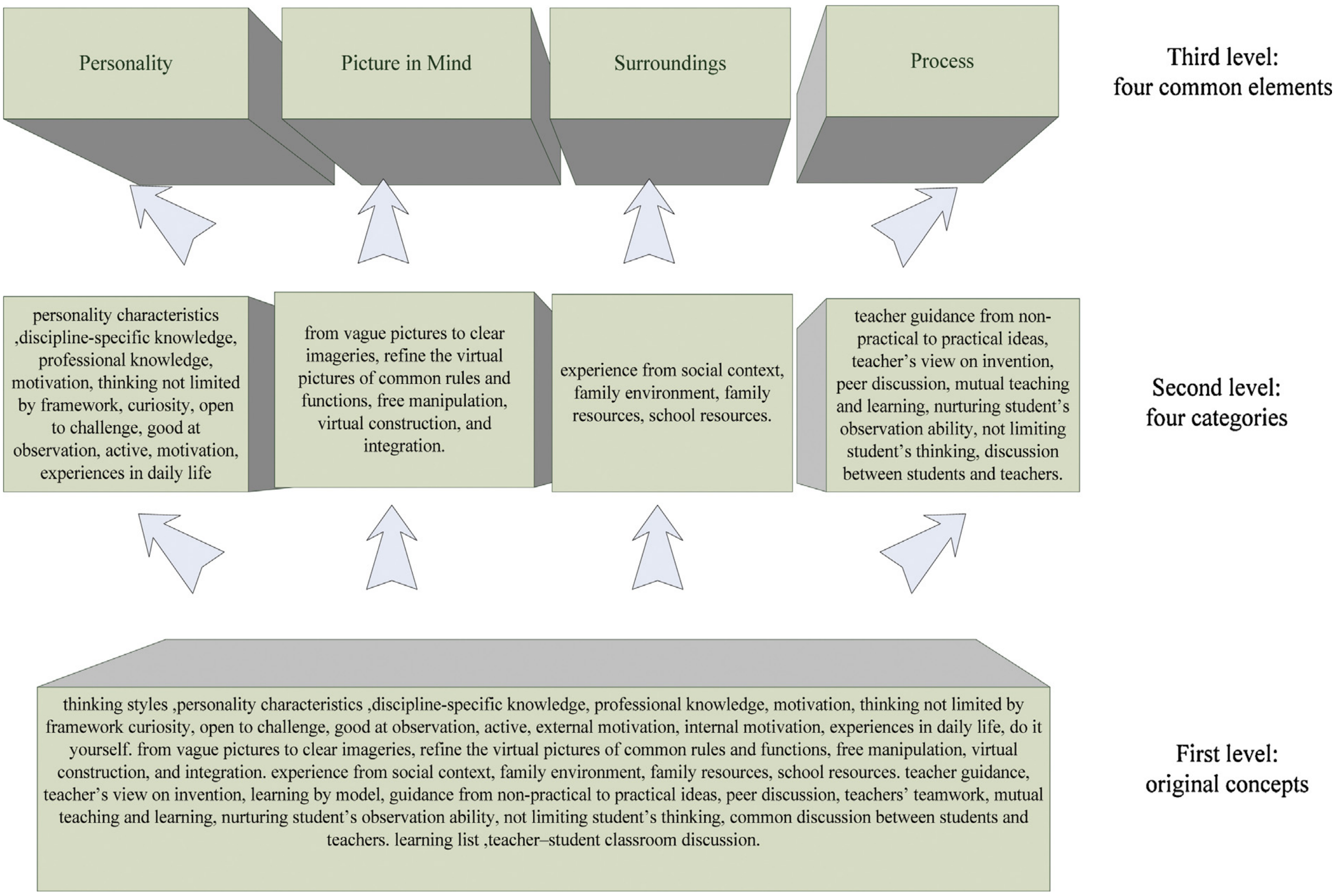

Fig. 4. The process for developing the 3PS model of scientific imagination.

guide students in finding associations among ideas. Furthermore, teachers judge the feasibility of students' ideas using both discipline-specific knowledge and life experience, and they teach students how to effectively discuss the matter of whether specific ideas can be practically accomplished. Furthermore, the use of interactive discussion with students provides teachers the opportunity to accrue knowledge about the occupations and backgrounds of the students' relatives and friends, providing them with new content that may become useful as a teaching method for inspiring students to succeed in self-proposed innovations. For example, teachers guide students to further consider the feasibility of selected ideas by asking learners such questions as "What functions and parts can be added or modified?"; "Is this right?"; "Will it be better if we modify it this way?"; and so on.

3.1.3. Virtual implementation stage

After proposing novel ideas, students enter the virtual implementation stage. The major operational abilities in this stage are conceptualisation, organisation, and formation (see Fig. 4). Using these abilities, students identify the excellent ideas from among the previously generated novel ideas. Students discuss whether given ideas can effectively solve problems in life, whether the ideas are feasible from a practical viewpoint, and whether the ideas are consistent with similar perspectives that have arisen in the past. The teaching methodology during this stage includes having students make their ideas concrete by presenting them verbally or visually (e.g., creating drawings that depict their ideas). This process requires students to consider several project-related issues such as choosing materials, devising procedures to assemble parts, determining the best mode to use to express desired functions, and more, all of which are necessary to generating a final draft of the design diagram.

Both internal and external factors affect this stage. Most influential among the internal factors in this stage are the individuals' ability relative to the project and the individual's ability to effectively convey or express ideas. Effective expression requires communicating ideas concretely, clearly, and thoroughly so as to effectively provide the listener with information. Furthermore, students who are persistent and observant may realise even greater benefits as they experience the scientific imagination process. Persistence appears to foster the development of an attitude of openness towards unfamiliar phenomena and confrontations with challenging circumstances. Both persistence and the ability to be observant are useful internal resources for attaining mastery of the skills and abilities that are the foci during this stage. These specific characteristics are useful, and perhaps even essential, to successfully learning scientific imagination, particularly among elementary school-aged students, whose developmental level imposes limitations on their abilities, (e.g., limited school-based knowledge, fewer operational skills due to their developmental status, etc.). Therefore, elementary school students face certain difficulties in seeing the products of their scientific imagination realised. During the discussion process of design diagram modification or prototype production, a certain level of persistence is needed. Persistence helps students to continue with the learning task and not give up when they encounter difficulties and challenges, and it enables them to use their experience of the scientific imagination learning process as a reference when considering the possible effects of applying an idea in practical problem solving.

External factors include social resources, teacher-directed activity, and teacher–student discussions. In terms of social resources, parents likely have the greatest influence with school-aged children. With regard to teacher-directed activity and teacher–student discussion, students can receive help in completing the final draft of their design diagrams by participating in teacher–student discussions and attending to instruction provided by teachers. For example, Teacher B noted that, after the students were taught the tasks in the virtual implementation stage, they generated some initial novel ideas and then conveyed their ideas concretely by drawing representations of the prototype. After expressing their ideas visually, the students engaged in both teacher–student and student–student discussions, which helped the students in modifying select portions of their design diagrams. The observations made by Teacher B during the example described above appeared to indicate an interdependent relationship between the virtual implementation stage and students' success in producing a prototype of their individual creation or invention, as required by the scientific imagination learning process. On the other hand, many IEYI award-winning teachers maintained the perspective that instruction in conceptualisation, organisation, and formation are more appropriate for elementary school students than for older students. When teaching scientific imagination, not every step need be followed, and instruction need not proceed in the same sequence. In instructing some students, teachers may find it to be more effective to begin the process of teaching scientific imagination by having students express their design diagram in writing and/or drawing. This may be followed by the teacher's guiding students in the implementation of their chosen ideas through activities that include selecting materials, assembling parts of the innovation, and identifying its desired functions. Some students feel greater success when instruction affords them the opportunity to initially express ideas verbally, followed by depicting design diagrams through drawings, and concluding with activities showing the implementation of those ideas that ultimately resulted in developing their design diagrams. Additionally, the sequences may be different for older students. This potentially different sequence needs to be verified by further studies.

In summary, the scientific imagination process has different characteristics in different stages. Quantitative changes can be seen within the same stage, as well as qualitative leaps between stages. Each individual goes through the three stages of the scientific imagination process: initiation, dynamic adjustment, and virtual implementation. This is a cyclic process, and final products of different quality and quantity are generated under different conditions. Finally, ideas are transformed from imagination into creation as they are implemented and products are created.

3.2. Scientific imagination model

Through five expert panel discussions focused on the three stages of scientific imagination, the senior teachers identified and refined some important concepts in each stage based on their previous teaching experiences. This study was primarily based on the information provided by the five discussions noted above, supplemented by Ho et al.'s (2013) findings, interviews, and classroom observations. A category was created when two members of the research team placed similar responses in the same category. A peer review revealed an agreement of .7 for this classification method (Miles & Huberman, 1994). Use of this method of thematic categorisation (Miles & Huberman, 1994) to continually examine different data and theories revealed that four common elements affect individuals' scientific imagination in each stage (Fig. 4): personality, developmental process, picture-in-mind, and surroundings, which we named the 3PS model of scientific imagination based on the results of the data analysis. The contents of these four elements will be illustrated in the following paragraphs:

3.2.1. Personality

Imagination is universal among all individuals. However, there are differences in how individuals use imagination, resulting in variations in the ability to conceptualise ideas and to foresee the potential of a given idea when others are unable to do so. Based on analyses of students engaging in the process of learning and the development of imagination, as understood through interviews conducted with award-winning teachers, successful mastery of the scientific imagination process, as evidenced by higher academic performance, is observed in students who exhibit specific characteristics: ease of identifying associations, keen observational skills, curiosity, active involvement, the inclination to take the initiative, openness towards challenges, the ability to expand cognitive capacities to assimilate newly presented information without submitting to externally imposed frameworks or traditional models, and so on. Under the guidance of teachers' instructions, they more successfully initiate and expand on ideas, engage in productive teacher–student and peer–peer discussions, generate novel ideas, and create a final product or innovation by realising excellent ideas.

Among these characteristics, free association refers to the ability to permit ideas to emerge or come to mind based on higher-level abstract concepts that are generally seen as inaccessible for the individual at a given stage based on the developmental theory that young children's thinking capacity increases and expands as they become older. Individuals with keen observational skills are aware of the people and circumstances around them and care about common daily events. Furthermore, the ability to be observant encompasses the skill to find or recognise associations between ordinary objects or events and scientific principles. Curiosity refers to the ability to show interest in unfamiliar or novel objects or events and to develop an understanding of those novel things, and it also entails a desire to be connected to one's surroundings and to the other people who inhabit one's environment. The ability to be active and show initiative refers to having a generally positive stance combined with a strong desire that useful applications be found. Such an individual uses the strength of his or her will towards achieving a specific desired outcome. The characteristic referred to as openness and being open to challenges describes a person who has a sense of certainty and confidence that she or he is capable of finding and implementing solutions to unresolved matters. It also includes the belief that others see the solution of such problems as impossible. The characteristic of not being limited by a framework refers to the individual's ability to allow for exceptions to standard frameworks. Finally, enjoyment simply describes an individual's ability to take pleasure from his or her surroundings.

Not every student has all of these characteristics. However, appears that, among a group of students, at least one possesses these qualities. A student such as this has the ability to freely generate novel ideas and finds their realisation much easier than do others. These students more frequently raise examples based on their observations in daily life. They have an intense degree of curiosity about many and varied phenomena. They are inclined to actively take the initiative during the process of creating products. When they encounter difficulties, in addition to seeking information from their teachers, they are likely access other resources such as relatives, friends, and student peers. They may even collect information independently, relying on their own skills to find answers.

Comments from some of the teachers reflect these students' enjoyment of the process of scientific imagination:

D: There are very few students with these characteristics, but the products they make often show a great deal of imagination and creativity, because such students are constantly considering many ways to answer the questions. In other words, a higher degree of imagination and creativity is used only when the students are truly interested in the questions.
B: Your theory, and the assumption that it is indicative of a theoretical internal state called self-actualization, is a post hoc definition. From a psychological perspective, the students are actually having fun.
D: That's because the students are interested in the projects. They feel a sense of achievement after completing a project. It is through this process that self-actualization is realised (3_20110427).

3.2.2. *Developmental process*

At the core of the development of scientific imagination is the transformation of ideas generated from nothing. Based on this notion, we used concept mapping to confirm the scientific imagination process (Ho et al., 2013). The use of concept mapping can help us think about and differentiate relationships among the three stages of the scientific imagination process. It organises these concepts and integrates them in a systematic, hierarchical, and structured way through symbolic representation. Five panel discussions identified the common elements contributing to the scientific imagination process. However, each stage of the scientific imagination process involves unique concepts. For example, curiosity is the foundation of idea generation, and it motivates students to explore the life world. Students with abundant curiosity will become more familiar with the world. Additionally, the teaching strategy of "guiding without dominating" plays an important role in the virtual implementation stage. Teachers can help students concretise their ideas, such as by developing a draft or a prototype, rather than teach them how to so using the standard operating procedure.

3.2.3. *Picture-in-mind*

Picture-in-mind is considered one of the factors that affect an individual's scientific learning (Al-Balushi, 2009). During the development of each stage of scientific imagination, an individual forms various mental pictures that facilitate the operation of various abilities. These pictures start as divergent points and gradually become linked as they move from vague pictures to clear images. At first, students may encounter some inconveniences in life. Students generate many ideas in the Initiation stage, and the pictures in mind at this stage are messy, mixed, and fragmented; they are followed by various functional associations that are generated as they think about the problem. Then, in the dynamic adjustment stage, individuals start to search for associations among ideas and generate virtual pictures of common rules and functions. The following dialogue occurred between a teacher and a student.

E: How do you start your thinking? With your own ideas or with something else?
S: I start with my own stuff, and then the others', and finally the teachers' and the classroom's. In this way, I can come up with ideas.
E: Please describe it more specifically. For example, do you assemble the ideas while you are observing? Or do you just create a brand new thing that didn't exist before?
S: I just assemble what I have seen.
E: Is it like A + B + C?
S: Yes! It will be too hard for me to create a brand new thing.
E: Let me reconfirm what you're saying. You start to imagine whether it's possible to combine this and that. For example, paper plus pen. Is it correct?
S: Hmm. . . I start with watching, and I keep thinking what I can add on. That's about it. (From qualitative data in Ho et al., 2013)

Individuals then refine the virtual pictures of common rules and functions and form temporary mental images that can solve problems effectively. Finally, individuals further screen and reassemble these various temporary pictures by thinking through all plausible ways to achieve an appropriate and excellent image

In this study, we defined Picture-in-mind as the psychological ability to use imagination based on prior knowledge and experiences to create mental images of various scenes, pictures, or objects during the scientific invention process. This ability is characterised by free manipulation, virtual construction, and integration (Carroll, 1993; Han, Hung, & Tsai, 2008; Kozhevnikov, Michael, & Hegarty, 2007).

3.2.4. Surroundings

In terms of external environmental factors, imagination requires rich materials from the living surroundings to deconstruct and reconstruct imagination (Cheng et al., 2010; Han et al., 2008). Several examples of the external factors are multi-sensory stimulation, a free atmosphere, necessary resources, and teacher incentives and awards (Gallas, 2001; Osborn, 1953; Wood & Endres, 2004; Zabriskie, 2004; Zarnowski, 2009). Ho et al. (2013) showed that the family environment, teacher guidance, peer interaction, and multiple life experiences (e.g., reading novels or science fiction, watching movies, playing, attending seminars, and travelling) were the main influences. Variables such as whether the family environment provides a supportive atmosphere and resources, whether teachers appropriately guide the thinking of students, whether teachers provides stimulation, and whether peers provide reciprocal questioning influence whether students will be encouraged and helped to develop scientific imagination that can lead to invention. All of these environmental factors affect the formation of personal characteristics and can increase the richness and breadth of daily life experiences.

A: Daily life experiences are personal observations. These observations can be from parents, relatives and friends, from personal travel, and from observations at school, which all count as life experiences.
R: Because individuals apply their daily life experiences. . .
B: It should be applications of personal daily life experiences.
R: For personal daily life experiences, the experiences come from. . .
B: We are now using the teacher guidance method. . .
C: If it is not an observation, then it is an appreciation. For 24 h a day, what objects do I use? What do I use at home that I consider inconvenient? These are personal experiences. If they are not counted as personal experiences, then they are life experiences. Life experiences, sibling interaction, backgrounds of the relatives, friends, and parents all belong to the family part. Social experiences may be the news that students read. Then it is more "life experiences" than "observation." Life experiences are from family and the society, such as shopping, travel, and news.
R: So there should be a subcategory of "life experience" under the "family" concept. . .
C: That is, we limit problems to those encountered in the family and others encountered in the society. These included more than the siblings, relatives and friends, and parents encountered in the family. There should be more. . . Personal life experiences not related to the society are encountered by each individual. There are social experiences other than life experiences from family life. . . (4_20110518).

Thus, personality includes characteristics identified as potentially helpful for future research on the process of scientific imagination. Developmental process refers to the structure of the operations underlying the scientific imagination; these develop sequentially and can be taught and learned in stages. Picture-in-mind refers to the functions of mental images in the process of scientific invention. Finally, surroundings refer to those environments that facilitate the development of imagination.

4. Conclusions and suggestions

Now is the prime time to emphasise imagination and creativity in science education. Imagination and creativity dominate the changes in the current economy and culture (McCormack, 2010). From the perspective of scientific education, student-centred science or invention competitions extend the teaching curriculum and can deepen and broaden students' scientific concepts and technological skills. These extended science curricula operate through teachers' organised guidance and students' use of their thinking, manual skills, and oral expression, and they allow students to actively construct scientific concepts, understand the nature of problem solving, increase technological skills, and develop the ability to think independently, problem solve, and invent (Bencze & Bowen, 2009). Therefore, further integration of imagination into current science education will not only promote students' abilities in life (Church, 2006) but also help science teachers to increase their professional knowledge in teaching. This integration can be achieved by participation in various scientific pursuits, such as the invention process, which stimulate students' imagination under the guidance of teachers. During such activities, teachers can continuously provide students with opportunities to explore and can encourage students to learn more, to try to find the best answers for problems, and to generate ideas for positive products (Cheng, Li, & Liu, 2008; Cheng & Wang, 2002).

Finally, we propose that scientific imagination be integrated into existing natural science curricula and that our framework serve as a guide and frame of reference for those who teach these courses. In this study, we constructed concept maps of the scientific imagination process not only to help understand the factors that influence the guidance provided by teachers during the process whereby students develop scientific inventions, but also to help teachers refine their teaching strategies and provide a theoretical foundation for future imagination research. Furthermore, we developed the 3PS model of scientific imagination via a comprehensive interpretative process. We suggest that future research utilise this 3PS theoretical model of scientific imagination to create a checklist for each stage in the process of teaching scientific imagination. This checklist can provide targets for courses on scientific imagination. In the future, we plan to create a set of scientific imagination courses and models for their assessment to assist those who teach scientific imagination based on the 3PS model.

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References

Adams, J. (2004). The imagination and social life. *Qualitative Sociology*, *27*, 277–297. http://dx.doi.org/10.1023/B:QUAS.0000037619.28845.ef

Al-Balushi, S. M. (2009). Factors influencing pre-service science teachers' imagination at the microscopic level in chemistry. *International Journal of Science and Mathematics Education*, *7*, 1089–1110. http://dx.doi.org/10.1007/s10763-009-9155-1

Bencze, J. L., & Bowen, G. M. (2009). A national science fair: Exhibiting support for the knowledge economy. *International Journal of Science Education*, *31*, 2459–2483. http://dx.doi.org/10.1080/09500690802398127

Carroll, J. (1993). *Human cognitive abilities: A survey of factor-analytical studies*. New York: Cambridge University Press.

Cheng, Y. Y., & Wang, W. C. (2002). Factors that influence creativity behavior for awarded-winning teachers in scientific competitions (in Chinese). *Research in Applied Psychology*, *15*, 163–189.

Cheng, Y. Y., Li, Y. C., & Liu, K. S. (2008). The relationship between awarded teachers' teaching behavior and pupils' performance on creativity and problem solving in science subject (in Chinese). *Journal of Education & Psychology*, *31*, 1–30.

Cheng, Y. Y., Wang, W. C., Liu, K. S., & Chen, Y. L. (2010). Effects of association instruction on fourth graders' poetry creativity in Taiwan. *Creativity Research Journal*, *22*, 228–235. http://dx.doi.org/10.1080/10400419.2010.481542

Chiou, C. C. (2008). The effect of concept mapping on students' learning achievements and interests. *Innovations in Education and Teaching International*, *45*, 375–387. http://dx.doi.org/10.1080/14703290802377240

Church, E. B. (2006). Let's invent. *Scholastic Parent & Child*, *13*, 28–35.

Cruz, H. D., & Smedt, J. D. (2010). Science as structured imagination. *Journal of Creative Behavior*, *44*, 29–44. http://dx.doi.org/10.1002/j.2162-6057.2010.tb01324.x

Denzin, N. (1978). *Sociological methods: A source book* (2nd ed.). New York: McGraw-Hill.

Dílek, D. (2009). The reconstruction of the past through images: An iconographic analysis on the historical imagination usage skills of primary school pupils. *Educational Sciences: Theory & Practice*, *9*, 665–689.

Douville, P. (2004). Use mental imagery across the curriculum. *Preventing School Failure*, *49*, 36–39.

Eckhoff, A., & Urbach, J. (2008). Understanding imaginative thinking during childhood: Sociocultural conceptions of creativity and imaginative thought. *Early Childhood Education Journal*, *36*, 179–185. http://dx.doi.org/10.1007/s10643-008-0261-4

Gallas, K. (2001). Look, Karen, I'm running like Jell-O: Imagination as a question, a topic, a tool for literacy research and learning. *Research in the Teaching of English*, *35*, 457–492.

Grant, E. (2004). Scientific imagination in the middle ages. *Perspectives on Science*, *12*, 394–423. http://dx.doi.org/10.1162/1063614042776021

Han, C. C., Hung, L., & Tsai, C. L. (2008). Exploring connection between the mind's eye and reality – Cognitive neuroscience advances in the relationship of perception and mental imagery. *Science Education Monthly*, *308*, 16–23.

Ho, H. C., Wang, C. C., & Cheng, Y. Y. (2013). Analysis of scientific imagination process. *Thinking Skills and Creativity*, *10*, 68–78. http://dx.doi.org/10.1016/j.tsc.2013.04.003

Johnson, R. B. (1997). Examining the validity structure of qualitative research. *Education*, *118*, 282–292.

Koestler, A. (1964). *The act of creation*. NY: Macmillan.

Kozhevnikov, M. M., Michael, A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, *31*, 549–579. http://dx.doi.org/10.1080/15326900701399897

Langer, E. (1993). A mindful education. *Education Psychologist*, *28*, 43–50. http://dx.doi.org/10.1207/s15326985ep2801_4

LeBoutillier, N., & Marks, D. F. (2003). Mental imagery and creativity: A meta-analytic review study. *British Journal of Psychology*, *94*, 29–44. http://dx.doi.org/10.1348/000712603762842084

Lin, W. W. (2011). The nurture of imagination and creation: Arkki, School of Architecture for Children and Youth in Republic of Finland. *Elementary Education*, *51*, 62–72.

Long, S. A., Winograd, P. N., & Bridge, C. A. (1989). The effects of reader and text characteristics on reports of imagery during and after reading. *Reading Research Quarterly*, *24*, 353–372.

Lothane, Z. (2007). Imagination as reciprocal process and its role in the psychoanalytic situation. *International Forum of Psychoanalysis*, *16*, 152–163. http://dx.doi.org/10.1080/08037060701278636

Maxwell, J. A. (1996). *Qualitative research design: An interactive approach*. London: Sage.

McCormack, A. J. (2010). Imagine and invent: Create a great future. *Journal of College Science Teaching*, *22*, 14–15.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis* (2nd ed.). Thousand Oaks, CA: Sage.

Mountain, V. (2007). Educational contexts for the development of children's spirituality: Exploring the use of imagination. *International Journal of Children's Spirituality*, *12*, 191–205. http://dx.doi.org/10.1080/13644360701467535

Osborn, A. (1953). *Applied imagination*. New York: Charles Scribner's Sons.

Pelaprat, E., & Cole, M. (2011). Minding the gap: Imagination, creativity and human cognition. *Integrative Psychological and Behavioral Science*, *45*, 397–418. http://dx.doi.org/10.1007/s12124-011-9176-5

Reijnders, S. (2010). Places of the imagination: An ethnography of the TV detective tour. *Cultural Geographies*, *17*, 37–52. http://dx.doi.org/10.1177/1474474009349998

Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. *Journal of Research in Science Teaching*, *33*, 569–600.

Stenbacka, C. (2001). Qualitative research requires quality concepts of its own. *Management Decision*, *39*, 551–555.

Trochim, W. M. K. (1989). An introduction to concept mapping for planning and evaluation. *Evaluation and Program Planning*, *12*, 1–16.

Vygotsky, S. L. (1930/2004). Imagination and creativity in childhood. *Journal of Russian and East European Psychology*, *42*, 7–97. http://dx.doi.org/10.2753/RPO1061-0405280184

Ward, T. B. (1994). Structured imagination – The role of category structure in exemplar generation. *Cognitive Psychology*, *27*(1), 1–40. http://dx.doi.org/10.1006/cogp.1994.1010

Wood, K. D., & Endres, C. (2004). Motivating student interest with the imagine, elaborate, predict, and confirm (IEPC) strategy. *Reading Teacher*, *58*, 346–357. http://dx.doi.org/10.1598/RT.58.4.4

Zabriskie, B. (2004). Imagination as laboratory. *Journal of Analytical Psychology*, *49*, 235–242. http://dx.doi.org/10.1111/j.1465-5922.2004.00455.x

Zarnowski, M. (2009). The thought experiment: An imaginative way into civic literacy. *Social Studies*, *10*, 55–62. http://dx.doi.org/10.3200/TSSS.100.2.55-62