Chapter 12
Innovative Science Educational Neuroscience: Strategies for Engaging Brain Waves in Science Education Research

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Abstract Science educational neuroscience is a new discipline that integrates science education, psychology, and biological processes. The potential of science educational neuroscience is to bridge the gap of research trends, methodologies, and applications between science education and neuroscience, and to translate research challenges into opportunities. In this area, researchers combine science education and the fundamental techniques of cognitive neuroscience such as electroencephalograms (EEG), event-related potentials (ERPs) and functional magnetic resonance imaging (fMRI) to provide specific and objective suggestions to science learners, educators, and curriculum designers. In recent years, a lot of educational neuroscience researchers have focused on students' cognitive abilities and emotions by analyzing neuroscience data. However, few studies have highlighted students' science learning abilities and strategies by engaging neuroscience. Furthermore, the orientations of methodology, data analysis, and philosophy differ between science education and neuroscience. Although there are many research challenges to face, there are some studies that provide practical implications for engaging neuroscience in science education.

12.1 Introduction

Over the past decade, the interest in brain research has been growing in science education (Huang et al 2014; Liu et al 2015). An increasing amount of evidence from brain research has been applied in the explanation of science educational research, such as the research of Liu and Chang (2014). Furthermore, the findings from neuroscience research provide many insights into teaching and learning. This chapter introduces the "innovative research idea" of science educational neuroscience, the innovative research approach of science educational neuroscience, the applications of science educational neuroscience, and the implications and suggestions for learning and teaching.

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Before discussing the idea of science educational neuroscience, the limitations of the mind, brain, and education need to be clarified in this chapter. In 1966, Soviet philosopher Evald Ilyenkov claimed that the brain does not think, but a human being thinks with the help of his/her brain. He mentioned that the brain is an operational mechanism and that the mind controls that mechanism actively. David Bakhurst (2008) published a paper in the *Journal of Philosophy of Education* in which he discussed the philosophical views on the mind and the brain, indicating the importance of personal potential.

> ….First, my mental states are unified because they are all states of a particular person, me. Second, they are unified in that they express my orientation to the world, which comprises both a conception of how the world is and commitments to change the world in various ways through action…. (Bakhurst 2008, p. 422)

Combining these points of view through 1966 to 2008, the brain can be considered to be a biological machine, with the human mind seen as its operator. On the surface, it seems that the operator (the human mind) is more important than the machine (the human brain) in actual practice (educational practice). In reality, an operator could not operate a machine well without understanding its characteristics and limitations. For education, although the general teaching or learning strategies could help some students' learning, they could not improve all students' studying since each brain is unique. In view of this, Evald Ilyenkov suggested that the purpose of education is to improve every student's potential, but not to try to train their brains. David Bakhurst also mentioned the importance of adaptive development. Some talented or gifted students have inborn advantages of brain functions which allow them to learn well, and educators and teachers need to help them to develop their potential.

To help students to learn actively and to develop their own potential is one of the most important aims of education. In actual learning, students' minds could be seen as operators and their brains as machines. If we want to teach someone to operate a machine well, we need to thoroughly understand the characteristics and limitations of the machine. In other words, the characteristics and limitations of the human brain play a significant role in learning and teaching. That is the reason why we need to bridge the gap between neuroscience research and science education research, such that the linkage of these two domains will bring new insights regarding the practice of science education.

12.2 The Innovative Research Idea of Science Educational Neuroscience

The idea of bridging education and neuroscience can be traced back to the 1990s. In 1997, Bruer encouraged researchers from the two different domains of neuroscience and education to enter into a dialogue. However, at that time, Bruer felt that the distance between these two domains was too great. Byrnes (2001) also commented in 1994, the beginning of the application of brain research in education, that he did not believe that the results from neuroscience could reflect the reality of physiology and education. Thus, the idea of linking neuroscience and education arose in the 1990s, but the gap between the two was seen to be too great at that time.

From 1990 until now, many researchers have devoted their time to bridge this gap between neuroscience and education and achieved excellent results (Bakhurst 2008; Howard-Jones 2008; Prudy and Morrison 2009; Mason 2009; Willingham 2009; Coch and Ansari 2009; Carew and Magsamen 2010; Baker et al. 2012). Byrnes (2001) argued that the results from neuroscience could not reflect the reality of physiology and education was wrong. He found that many important theories of psychology and education, such as attention, memory, emotions, and reading comprehension, could be supported or judged from the evidence of neuroscience. Therefore, he wrote a book, "Minds, Brains, and Learning: Understanding the Psychological and Educational Relevance of Neuroscientific Research," that supports the importance of the linkage between neuroscience and education, and he also agreed that the psychology and education domains need to engage in neuroscience research. Purdy and Morrison (2009) and Baker et al. (2012) also argued that brain-based learning packages needed to be considered in school learning. It seems that the idea of educational neuroscience was gradually gaining emphasis.

From 2001 to 2014, there were 625 Taiwan theses and dissertations related to neuroscience and education (the data were collected from the System of National Digital Library of Theses and Dissertations in Taiwan). Although educational neuroscience was developing in these few years, Mason suggested that researchers needed to consider other educational phenomena and, in this chapter, we will focus on discussing the domain of science education. Science education is more concerned with engaging science contents and processing, and the branch of science learning needs students to use a lot of specific cognitive skills. Take the definition of 2D chemical structural formulas as an example; students need to memorize the chemical elements and the rules of chemical structures, and use their imagination and spatial ability to rotate the chemical structural formulas in their mind; then they can identify the 2D chemical structural formulas well (Huang and Liu 2013). In contrast, this ability of mental rotation is not used in learning Chinese or history, for example. Hence, the characteristics of science education and science learning are unique in the field of education.

Some cognitive processing of science learning depends on the brain's function and limitations. The example of the identification of chemical structural formulas shows that students need to use their spatial and mental rotation abilities to complete the task. Although such abilities could be trained, those talented and gifted students with innate spatial abilities should not be ignored (Liu et al , 2014b; Huang et al 2014; Liu et al 2015). Moreover, how these gifted students use their abilities to identify chemical structural formulas might be important reference material to use in training other students. In this case, the understanding of cognitive processing in students' science learning requires greater emphasis, and the engagement of neuroscience is a better way to help us to fully understand cognitive processing.

In this chapter, we suggest the innovative research idea of science educational neuroscience. Researchers do not need to understand all of the functions of the brain; neither do they need to carry out neuroscience research right now. What we suggest though is that researchers in the science education field could start to read the important findings of neuroscience and try to engage those findings in their science education research. We believe that the findings from neuroscience would provide many insights into science education research.

12.3 The Innovative Research Approach of Science Educational Neuroscience

The commonly used research approaches used in science education can be divided into quantitative and qualitative approaches (Liu et al , 2014a; Huang et al 2014). In the quantitative research approach, questionnaires and tests are used most, the data from which are analyzed statistically. In the qualitative research approach, open-ended questionnaires and interviews are commonly used. The data from open-ended questionnaires are often scored by experts in the corresponding fields, and the scores are also analyzed statistically. The interview data are generally tape-recorded and then transcribed verbatim. The contents of the verbatim text are then coded according to the theoretical framework adopted by the researchers. Of course, if the researchers want to use grounded theory, the contents of the verbatim text will be categorized without expectations and be used to form the basis of the theory. The advantage of quantitative research is that it could collect huge amounts of data in a short time, and trends can be identified by analyzing these statistical data. On the other hand, the advantage of qualitative research is that it can collect detailed data which reflect individual differences. These two research approaches are complementary in science education research. Hence, an increasing amount of research in science education adopts mixed research methods to interpret the findings.

In this chapter, we agree that the quantitative and qualitative research approaches both need to be used in science education research. Moreover, we suggest that the neuroscience research approach is also worth engaging in science education research. The neuroscience research approach could collect individual brain activities and transfer these activities into statistical data. In other words, neuroscience data could be quantitatively analyzed with the detailed data from individuals. Further, the results of brain activity analysis will be additional evidence to interpret the findings of science education research. Based on this idea, we suggest that the innovative research approach of science educational neuroscience might combine the commonly used quantitative and qualitative research approaches, while also adding the neuroscience research approach.

The instruments of the quantitative research approach could collect the data that reflect the participants' choices after they make decisions. On the other hand, the instruments of the qualitative research approach could help us to understand why the participants decided to choose a specific answer. In this section, the key point is to emphasize the introduction of the neuroscience research approach.

The most commonly used neuroscience technologies in exploring students' learning are electroencephalograms (EEG), event-related potentials (ERPs), and functional magnetic resonance imaging (fMRI). EEG and ERPs are the procedures to measure the electrical activity in the cerebral cortex when a person carries out

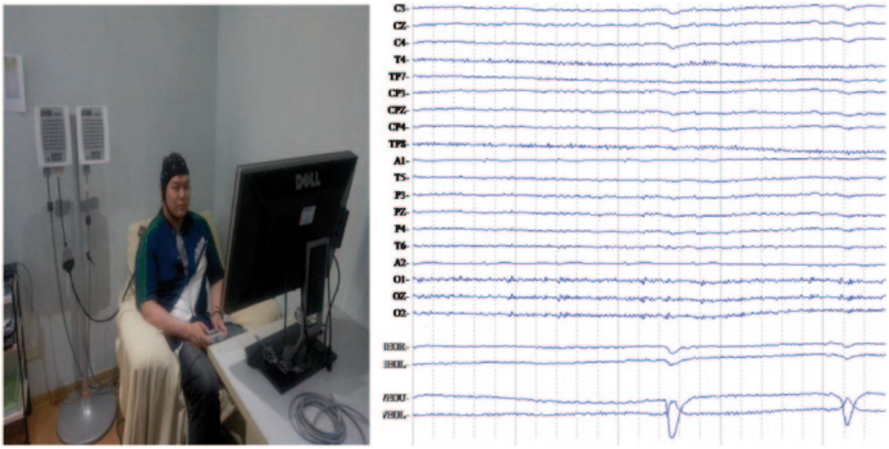
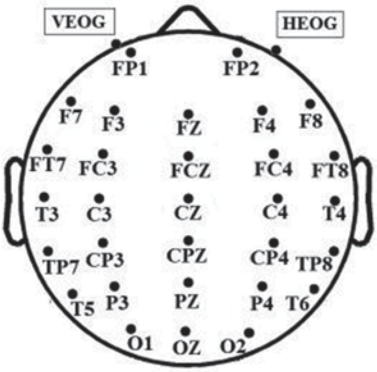


Fig. 12.1 The **a** procedure and **b** the raw data of EEG and ERPs

a task, and fMRI is the procedure to detect the location of electrical activity in the brain. Furthermore, the EEG methodology involves collecting the participants' normal biology responses when not performing cognitive tasks, such as opening and closing their eyes. On the other hand, the ERPs methodology is to collect the participants' specialized responses when doing assigned cognitive tasks, such as remembering or mental rotation. To sum up, the procedures and raw data are similar in the EEG and ERPs methodologies (Fig. 12.1), but the treatments of the two methodologies differ.

In the EEG or ERPs procedures, the participants need to wear an electrode cap (commercial electro-cap, Electro-Cap International, Eaton, OH) on their head before performing a set task (Fig. 12.1a). There are many kinds of Electro-Cap used in EEG or ERPs experiments; the most commonly used are 36 channel, 128 channel, and 256 channel. In educational research, we recommend that the 36 channel Electro-Cap is sufficient to collect the data of human cognitive processing. Figure 12.2 shows the assigned symbols, numbers, and locations on the Electro-Cap. The

Fig. 12.2 The electrode sites of the electrode cap



HEOR and HEOL indicate the horizontal electro-oculogram (EOG), and the VEOU and VEOL data record the vertical EOG. The data from these four electrodes could help to adjust the brain wave by excising the effect of the tremble from the muscles around the eyes when the subject reads the tasks on the computer screen or blinks. The other EEG raw data are shown as serial symbols and numbers in Fig. 12.2, such as C3, CZ, C4, etc. These symbols and numbers follow the 10–20 international system. For example, the symbol “F” is located in the frontal lobe of the brain area, the odd numbers (1, 3, 5, and 7) are located in the left brain hemisphere, and the even numbers (2, 4, 6, and 8) are located in the right brain hemisphere.

Although the EEG and ERPs technologies could show the brain areas where the data are located in the brain, fMRI has higher location resolution of the brain areas than EEG and ERPs. On the other hand, the EEG and ERPs have higher time resolutions of cognitive processing than fMRI. EEG, ERPs, and fMRI each have their strengths and weaknesses, but EEG and ERPs are more commonly used because of their cheaper price and greater convenience compared with fMRI.

The cerebral cortex is one of the most important structures in the human brain. It deals with the transferring and presenting of the processing of consciousness, sense perception signals, and actions. The EEG and ERPs technologies could collect the electrical activity from the cerebral cortex of the whole brain, and the results could reflect what kind of cognitive abilities the participants used in completing the cognitive tasks. In identifying the EEG and ERPs data from the cerebral cortex, the researchers need to consider where these data are located in the brain areas since the different brain areas respond to different functions (Fig. 12.3).

In Fig. 12.3, the four brain areas of the cerebral cortex respond to different cognitive functions. Table 12.1 shows a brief categorization. We must remind the readers that Table 12.1 is a simple classification, and that they need to read specialized books and journal papers to thoroughly understand the theories of the human brain and cognitive processing.

The electrical activity from the cerebral cortex in different brain areas could provide biological evidence to help researchers infer participants’ cognitive processing. We suggest that science researchers should reference the findings from neuroscience and combine the results from quantitative and qualitative research methods to create an innovative research approach of science educational neuroscience. This would provide more integrated annotations than adopting the single research methods for interpreting the findings of science education.

Fig. 12.3 The four brain areas of the cerebral cortex

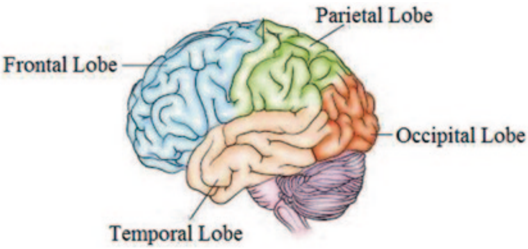


Table 12.1 The corresponding brain areas and cognitive functions

Brain areas	Cognitive functions	Education applications (examples)
Frontal lobe	Specialized verbal or reading abilities, memory, attention, emotions, reasoning	Reading skills, reading strategies, learning motivation
Parietal lobe	Memory, attention and mathematics abilities	Learning attention, number sense, mathematics problem solving
Occipital lobe	Visual processing, working memory about spatial abilities	Spatial abilities about chemistry, physics or mathematics
Temporal lobe	Auditory processing, emotions, working memory	Emotions about learning, verbal abilities about learning

12.4 The Applications of Science Educational Neuroscience

In recent years, researchers have strived to apply the findings from neuroscience to interpret the phenomena of science learning and science education, with interesting results.

12.4.1 Emotion and Scientific Creativity

In the science education research domain, Petty and Cacioppo (1986) found that positive emotions improve a person's scientific creativity, but there are no statistically significant differences between scientific creativity and negative emotion. However, the study findings from George and Zhou (2002) indicated that negative emotions could improve students' performance of scientific creativity. In 2006, Filipowicz performed similar research and suggested that students' performance of scientific creativity is affected by positive emotion in some cases and by negative emotion in others. Why are the results of these studies so different? The first concern in these studies might be: "Do these students really experience the assigned emotions before they exhibit scientific creativity?" In studies on emotion, it is not in fact possible for the researchers to be certain of the participants' emotions at the time of performing the set tasks. We could let the participants self-report their emotions, but how can we confirm the reliability and validity of their self-reports? We can never be certain of the participants' real emotions at the exact moment of testing. To overcome this difficult situation, Huang et al. (2008) used the EEG methodology to detect the participants' emotions throughout the testing. They chose 30 pictures from the international affective pictures system (IAPS) to induce the participants' affect. Of these 30 pictures, 10 were designed to elicit positive emotions, 10 were to elicit negative emotions, and 10 were neutral in that they did not reflect any emotion (Fig. 12.4). Each participant needed to take part in the three affect experiments individually while wearing an electrode cap to collect the EEG data. After the participants took part in one affect experiment, they completed a questionnaire

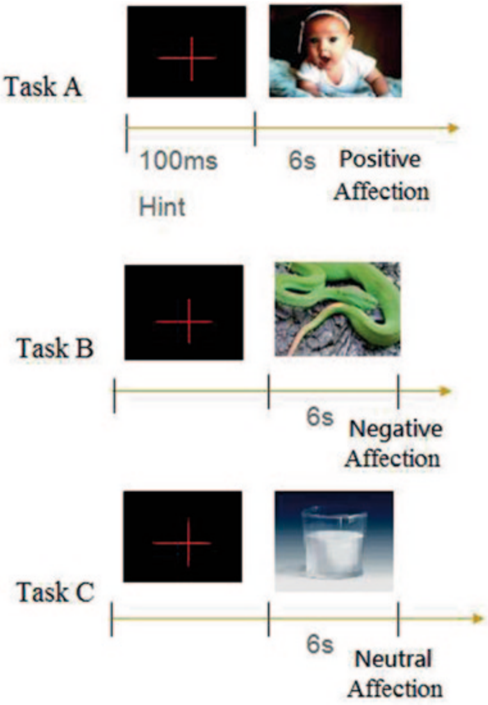


Fig. 12.4 Examples of pictures from IAPS (Huang et al. 2008)

of scientific creativity. Hence, the participants needed to complete three scientific creativity questionnaires which had similar validity, reliability, and consistency. The participants were asked to take a rest between each of the three experiments. The EEG data could ascertain whether the participants did indeed show the assigned emotions. If they did not show the assigned emotions, the data would be rejected.

The results from Huang et al.'s study indicated that scientific creativity will show greater improvement when positive and negative emotions are being experienced than when feeling neutral emotions (Fig. 12.5). They also found that students' performance of scientific creativity is better with negative than with positive emotion. The findings from Huang et al.'s study supported the results of Filipowicz's study.

It could be questioned, since the IAPS is a reliable instrument to induce participants' emotions, why researchers need to use it in combination with EEG methodology. The reason is that researchers need to seek more meticulous and detailed data in science education research. Although the IAPS has higher reliability than other instruments in inducing participants' emotions, individual differences still exist. Take Fig. 12.4 as an example; the second picture is a snake. Of course, most people will feel fear while viewing a picture of a snake, and that fear would be a negative emotion. However, there are always those people who may feel excited when they see a picture of a snake, which would be a positive emotion. With neuroscience research, we can reject the exceptional cases and command the variables well, thus making the findings and results more reliable and powerful.

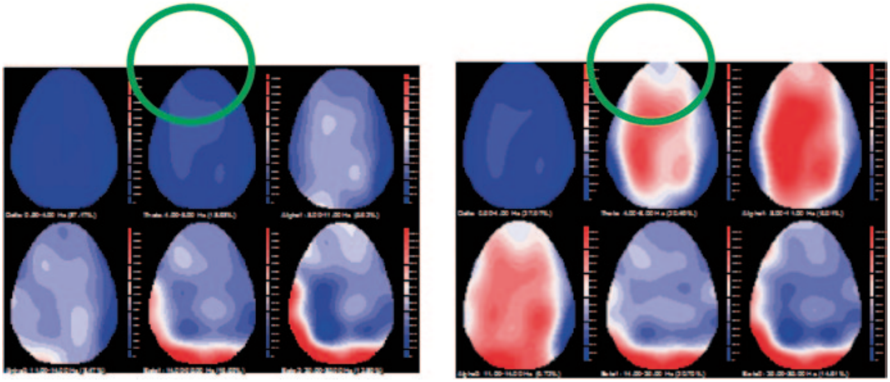


Fig. 12.5 An example of EEG data with emotional reflection: **a** *left* figures: neutral emotion; **b** *right* figures: positive emotion (Huang et al. 2008)

Based on the results of emotions and scientific creativity, further research on affect will be discussed. Many studies have indicated that some students fear facing traditional written tests; therefore, they have tried to help these students to overcome their negative affect by testing them by computer. The next section will discuss neuroscience research on affect and computer-based learning.

12.4.2 Affect and Computer-Based Learning

Self-assessment is an important issue in the evaluation of students' learning in the computer-based learning field. Based on the immediate responses of computer-based learning, affective reflection has been added to computerized self-assessment to promote students' learning motivation in the recent few years (Cassady and Gridley 2005; Economides 2009; Nicol and Macfarlane-Dick 2006).

In order to promote students' positive emotion in computerized self-assessment, Moridis and Economides (2012) adopted applause as an achievement-based reward in a test. The results of their study indicated that the male students performed better in the test with applause than without, but there was no significant difference for the female students.

In the case of this study, there could be two reasons why the female students did not perform better or worse in the test with applause than the one without applause. First, the treatment of applause did not induce the female students' positive or negative affection. Second, the applause might have induced the female students' specific affect, but the affect did not help them to learn better. Neither of these two possible reasons could be interpreted by questionnaires, tests, or interviews, but could only be detected by neuroscience methodology.

To find out the possible reasons why the female students did not perform better or worse in the test with applause than without applause, we designed a similar treatment by using EEG methodology in our lab (paper submitted for publication). Fifteen male and fifteen female students participated in our study. They were asked to solve mathematics problems with and without applause feedback. The results showed that both the male and female groups had higher alpha frequency power values when receiving the applause feedback; moreover, the brain activities of the male students were higher than those of the female students. Alpha frequency power is seen as an indicator proving the inducement of positive affect. The higher alpha frequency power indicated more positive affect. Hence, we can say that both the male and female students' positive emotions were induced by receiving the applause feedback, but the effect is larger in males than in females.

Furthermore, both the male and female students' delta frequency power values of their brain waves were higher when completing the controlled computer-assisted self-assessment test without applause feedback than for the test with feedback. The delta frequency in the frontal lobe of the brain could reflect humans' high-level cognitive processing (Ho et al. 2012). The higher delta frequency indicated more difficulties faced when the participants completed this task. To sum up, the results of delta frequency power indicated that both the male and female students did the mathematics task better with applause feedback than without it. However, for the female students, there was no significant difference in the delta frequency power between these two treatments.

In our study, we used the EEG methodology to identify the reasons why the female students did not perform better or worse in the test with applause than without, while the male students performed better. We proposed two hypotheses. First, we considered whether the treatment of applause induced the female students' positive or negative affect. The evidence from the neuroscience data (the increasing alpha frequency power) showed that the applause did in fact induce the female students' positive affect. However, the effect of inducing positive affect using applause is less in female than in male students. Second, we wanted to confirm whether the affect had an influence on the students' learning. The evidence from the neuroscience data (the increasing delta frequency power) showed that the positive affect could indeed help students to learn better and more easily. Therefore, in conclusion, we supported that the applause feedback with computerized self-assessment could help to improve students' positive affect and promote their performance in mathematics tests. However, the applause feedback is more useful for male students than for females since it could not induce sufficient positive affect in the female students.

In this section, we find that gender differences will influence the performance of science learning. Further, we hypothesize that some specific cognitive skills will exhibit individual differences, and we suppose that these cognitive skills will affect students' science learning performance. The next section will provide research findings about mental rotation and chemistry learning, and discuss the influences of students' science learning performance on the differences in specific cognitive skills.

12.4.3 Mental Rotation and Chemistry Learning

Chemistry is a difficult subject for students to learn since it involves many abstract concepts, symbols, and unfamiliar specific terms (Gilbert and Treagust 2009; Tsaparlis et al 2010). One of the basic areas of knowledge in learning chemistry is chemical structural formulas. Unfortunately, many students cannot identify 2D chemical structural formulas well. In the science education domain, there are different opinions as to why some students can identify such formulas well while others cannot.

> Many researchers mentioned that mental rotation would affect the identification and learning of chemical structural formulas (Korakakis et al. 2009; Mayer 2001; Shubbar 1990; Wu et al. 2001). However, some researchers argued that low-achieving students may need to identify chemical structural formulas with mental rotation……As Larkin, McDermott, Simon and Simon (1980) mentioned in their study, participants who were experts in science reported that they could solve problems and form mental images which included 2D and 3D representations in their field without using mental rotation strategies…It seems that the role of mental rotation in identifying chemical structural formulas is not clear based on the research discussed above." (Huang and Liu 2012, p. 38)

From the results of previous studies, the effects of mental rotation are not clear in chemical structural formula identification. Therefore, Huang and Liu adopted ERPs to detect the participants' use of mental rotation in identifying chemical structural formulas. They adopted a chemical conceptual questionnaire, ERP experiments and interviews in their study which were administered to 18 university students in Taiwan. By analyzing the neuroscience data they found that both high- and low-achieving students used mental rotation cognitive processing to identify 2D and 3D chemical structural formulas. In other words, their findings supported that mental rotation does in fact affect the identification of chemical structural formulas. Then, through analysis of the interview data, they found that both high- and low-achieving students used similar strategies of mental rotation in identifying 3D chemical structural formulas, but they used different strategies of mental rotation to identify 2D chemical structural formulas. They found:

> … low-achieving students used similar strategies to identify 2D chemical structural formulas as they did to identify 2D figures because they did not realize that the 2D chemical structural formulas were the projections of 3D chemical structural formulas. On the other hand, the HSG students used different strategies to identify 2D figures and 2D chemical structural formulas because they understand that the concepts of 2D figures and 2D chemical structural formulas are different. (Huang and Liu 2012, p. 51)

Furthermore, Huang and Liu (2013) analyzed other neuroscience data and indicated that the chemical element symbols are meaningless for low-achieving students. This would be another reason why they could not identify chemical structural formulas well.

Huang and Liu's study provides new, biological evidence to support the belief that mental rotation affects the identification of chemical structural formulas, and provides reasons why some students fail to identify the chemical structural formulas through the interviews. Their study not only provides a new insight into science education research, but also raises some objective suggestions for science education. From the results of Huang and Liu's study, we may suggest that the training of students' identification of chemical structural formulas should first involve training their cognitive processing of mental rotation, and then help them to understand the translation between 2D and 3D chemical structural formulas by the use of virtual and real models. In other words, we agree that it is important to teach students to use analytical strategies to identify chemical structural formulas, but the teachers also need to consider the basic cognitive strategies of mental rotation when teaching the strategies and materials related to chemical structural formulas.

12.5 Suggestions for Science Education

In this section, we provide some suggestions for science education researchers, and science teachers and educators.

12.5.1 The Challenges for Future Researchers

In this chapter, we have mentioned the new trends of combining research on neuroscience and science education, and we also made efforts to do the related researches (Liu et al 2014a; Liu et al 2014b; Huang et al 2014; Liu et al 2015). However, as interdisciplinary researchers, we need to provide information regarding the difficulties faced in the engagement of neuroscience and science education for future researchers. First of all, the validity of the methodologies and technologies of science educational neuroscience needs to be confirmed by professional science educational neuroscience experts but not only by neuroscience researchers, because they could supply suggestions from the perspectives of both science education and neuroscience and remind other scholars of the limitations of research in both fields. Second, the inferences of the evidences from neuroscience need to be explained carefully. Many results from neuroscience data could only explain physiological responses which do not involve thinking; these kinds of findings do not reflect human thinking and learning, which are fundamental for science education. Therefore, the findings from neuroscience evidence need to be inferred more carefully. Third, we suggested that scholars who intend to become interdisciplinary researcher need to realize the importance of team work, and make efforts to cooperate with professional groups. A well-experienced group could increase the quality of interdisciplinary researches and decrease the flaws in the research design. That is a particularly important suggestion for naïve researchers who are interested in joining the study on science educational neuroscience.

12.5.2 Suggestions for Science Education Researchers

In the fourth part of this chapter, we introduced some examples such as emotions and scientific creativity, mental rotation and chemistry learning, and affect and computer-based learning. All of these science educational studies raised research questions which required evidence from neuroscience data to interpret the results. The neuroscience data not only provided evidence to explain the results, but also provided objective suggestions for human learning. Hence, we suggest that science education researchers need to focus on the new findings of neuroscience and apply this evidence to interpret the findings in science education research. It is not necessary to understand all of the theories regarding the human brain or neuroscience, but to apply the important results in science education would provide many insights. To comprehend the innovative research ideas of science educational neuroscience might be the first step. Applying the important results from neuroscience that interpret the findings of science education might be the second step. Finally, researchers could try their best to develop strategies for engaging neuroscience methodology in science education research.

12.5.3 Suggestions for Science Teachers and Educators

At the beginning of this chapter, we stressed that the most important purpose of education is to help students to learn actively and develop their potential. The same purpose is relevant in science education, which is more concerned with science content and processing than general education is. We mentioned at the beginning of this chapter that the human mind can be seen as the operator while the human brain is the machine. A science teacher or educator should clearly understand which cognitive abilities the students need to have to learn each science concept, and help the students to try their best to perform the corresponding cognitive abilities. Besides, science teachers and educators need to have a basic understanding of the human brain. At least, they need to know that the characteristics and limitations of each student's brain are different and unique, and their mission is to help each student perform their best.

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