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An Event-Related Potentials Study of Mental Rotation in Identifying Chemical Structural Formulas

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The purpose of this study was to investigate how mental rotation strategies affect the identification of chemical structural formulas. This study conducted event-related potentials (ERPs) experiments. In addition to the data collected in the ERPs, a Chemical Structure Conceptual Questionnaire and interviews were also administered for data collection. Eighteen university students majoring in chemistry were recruited. In the ERP experiments, the participants were required to identify 2D figures, 2D chemical structural formulas, 3D objects and 3D chemical structural formulas. The contours of 2D figures are similar to those of 2D chemical structural formulas, but they contain no content knowledge. Likewise, the contours of 3D objects are similar to 3D chemical structural formulas without content knowledge. The results showed that all students used similar strategies of mental rotation in identifying 2D figures, 3D objects and 3D chemical structural formulas. However, the high-achieving students used different strategies in identifying 2D figures and chemical structural formulas, while the low-achieving students tended to use similar strategies of mental rotation in identifying both 2D figures and chemical structural formulas. The results indicate that some of the difficulties in identifying 2D chemical structural formulas that students encounter are due to their inappropriate strategies of mental rotation. These results could guide teachers and curriculum designers to develop chemistry learning tools and teaching strategies which could promote students' understanding of chemical structural formulas and practice students' representational skills through mental rotation. Furthermore, this study suggests that ERP technology could be used in further studies to explore the effects of mental rotation on science learning.

Key words: Chemical structural formulas; Event-related potentials; Mental rotation; Rotation-related negativity

Chemistry is an important branch of science, but the abstract concepts and submicro representations of chemistry, such as atoms or molecules, make it difficult for students to learn (Özmen, 2004; Frailich, Kesner, & Hofstein, 2009; Gilbert & Treagust, 2009; Tsaparlis, Kolioulis, & Pappa, 2010). One of the most important and difficult topics in chemistry is chemical structures, because the concepts of chemical structures include both the abstract concepts and the submicro representations of chemistry, such as the concepts of atomic shape, molecular shape, chemical bonding, the octet rule, lattices and chemical reactions (Gilbert, Reiner, & Nakhleh, 2008). To promote the understanding of chemical structures, two-dimensional (2D) and three-dimensional (3D) models of chemical structural formulas have been developed in the past several years (Gilbert, 2008; Seddon & Eniaiyeju, 1986; Shubbar, 1990; Wu, Krajcik, & Soloway, 2001). However, many students have failed to form 3D mental images from viewing 2D chemical structural formulas and mentally rotating 3D images (Korakakis, Pavlatou, Palyvos, & Spyrellis, 2009; Mayer, 2001; Wu, Krajcik, & Soloway, 2001). One possible reason why students are not able to successfully form 3D mental images is that they are incapable of decoding the visual information provided by depth cues in the diagrams (Shubbar, 1990; Wu et al., 2001). Besides, students' inability to mentally track depth cues which include related sizes

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and angles might be the reason for their failure to use mental rotation when analyzing structural formulas (Shubbar, 1990; Wu et al., 2001). The failure of mental rotation can be an obstacle for students in terms of the identification and learning of chemical structural formulas.

Many researchers have mentioned that mental rotation affects the identification and learning of chemical structural formulas (Korakakis, Pavlatou, Palyvos, & Spyrellis, 2009; Mayer, 2001; Shubbar, 1990; Wu et al., 2001; Wu, Krajcik, & Soloway, 2001). However, some researchers have argued that low-achieving students may need to identify chemical structural formulas with mental rotation, whereas high-achieving students do not (Hegarty, 2004; Stieff, 2007). Stieff (2007) reported that high-achieving students may use specific analytical strategies to transform the spatial relationships between different representations of chemical structural formulas without employing 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, based on the research discussed above, the role of mental rotation in identifying chemical structural formulas is not clear. Thus, the main purpose of this study was to clarify how mental rotation strategies affect the identification and learning of chemical structural formulas. The research questions were as follows: what are the differences between high- and low-achieving students in their use of mental rotation in identifying 2D and 3D figures, and 2D and 3D chemical structural formulas?

Many cognitive processes are difficult to explain verbally, such as mental rotation, and people may not even be aware of the use of all cognitive processes (Bragh, 2000). Hence, some studies have suggested that the study of cognitive processes must combine neurophysiological methods with questionnaires and interviews (Wang, Chiew, & Zhong, 2010). Therefore, this study adopted event-related potentials (ERPs) as a neurophysiological method. ERPs is a procedure to measure the electrical activity of the brain through the skull and scalp (Coles & Rugg, 1995). When participants recognize or apply specific cognitive abilities such as memory or mental rotation to respond to stimuli, the corresponding electrical activities in the brain are induced (Liu, Huang, & Chou, 2010; Ho et al., 2012).

Previous neurophysiological research has suggested that humans show similar trends while responding to the same task in elicited ERPs, such as recognition, identification, mental rotation or problem solving (Cicconetti et al., 2007; Juckel et al., 2008; Lai, Lin, Liou, & Liu, 2010). For example, previous studies have found that when humans respond to a mental rotation task, the greater the angle of the stimulus, the larger the rotation-related negativity of ERP data that is shown (Heil & Rolke, 2002; Milivojevic, Johnson, Hamm, & Corbalis, 2003). Hence, it is suitable to combine ERP technology in this study. The details of ERPs and rotation-related negativity are discussed in the next section.

In this study, the ERPs supplied neuroscience data indicative of the effect of mental rotation when the students identified the chemical structural formulas. The students' initial concepts of chemical structural formulas were determined using a questionnaire, and they were divided into high- and low-achieving groups based on the scores of the questionnaires. The interview data were used to explore and double check the strategies they adopted.

To the best of our knowledge, this is the first study to provide concrete evidence of the effect of mental rotation on identifying chemical structural formulas using neurophysiological methods, a questionnaire and interviews. The results of this research suggest implications for the learning and teaching of strategies for identifying chemical structural formulas, especially the strategies of mental rotation.

Literature Review

Mental rotation in the identification of chemical structural formulas

Mental rotation is a typical psychological process to identify rotated objects in daily life (Núñez-Peña & Aznar-Casanova, 2009), and it is an important ability for scientists, engineers and artists (Moè, 2009; Peronnet & Farah, 1989). Wu and Shah (2004) claimed that mental rotation ability is needed when identifying 2D and 3D chemical structural formulas. To identify a 3D chemical structural formula, one needs to use the strategies of mental rotation to rotate the whole formula as if it were a 3D object. However, to identify a 2D chemical structural formula, one needs not only rotate the whole molecule mentally but also to rotate parts of molecules around single bonds between two atoms when comparing two similar molecules (Gilbert et al., 2008). For example, Fig. 1(A) shows an example of a task with 2D objects, and Fig. 1(B) presents the pictures of chemical structural formulas. In Fig. 1(A), the two objects are mismatched, but the two chemical structural formulas in Fig. 1(B) can be matched by rotating around the single C-C bond.

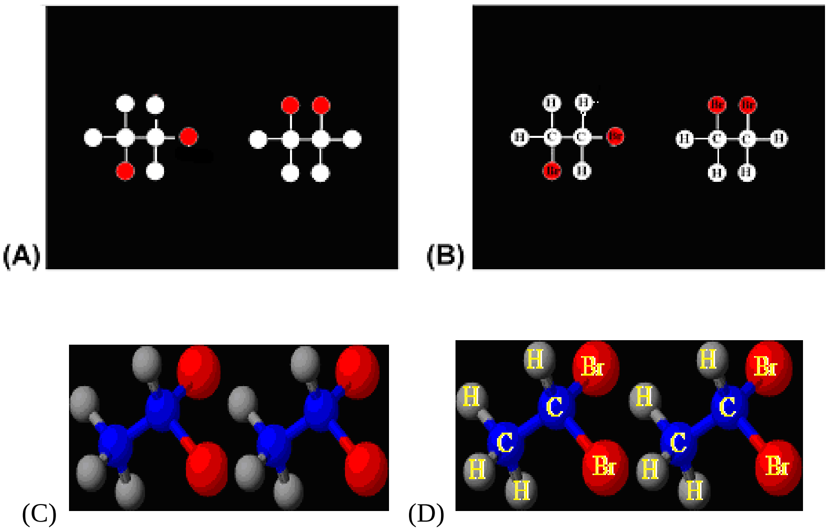


Figure 1. Examples of 2D and 3D pictures and 2D and 3D chemical structural formulas. (A) The 2D pictures are mismatched. (B) Both of the chemical structural formulas represent $C_2H_2Br_2$. (C) An example of a 3D picture. (D) An example of a 3D chemical structural formula.

Both of the chemical structural formulas shown in Fig. 1(B) represent $C_2H_2Br_2$. Six atoms surround the ‘C’ atoms. Every pair of atoms is connected by a bond that indicates “the force of attraction between two atoms” in chemistry. These bonds are abstract concepts that do not really exist, but which can be rotated around the ‘C’ atoms. The participants were not told whether the single bond could be rotated; they needed to make this judgment based on their background knowledge.

Many teachers and textbooks use balls and sticks to illustrate chemical structural formulas (Frailich et al., 2009; Stevens, Delgado, & Krajcik, 2010). Unfortunately, many students believe that a chemical bond is a real physical entity because of these ball-and-stick models (Boo, 1998; Butts & Smith, 1987), and tend to use daily life experience with real objects to help them rotate the chemical structural formulas (Mathewson, 1999, Moè, 2009; Núñez-Peña & Aznar-Casanova, 2009; Stevens et al., 2010). The strategies of mental rotation which are used to identify 3D figures (Fig. 1(C)) could be the same as those used to identify 3D chemical structural formulas (Fig. 1(C)). However, the strategies of mental rotation are different when identifying 2D figures and 2D chemical structural formulas.

Hence, this study also incorporated a task in which 2D figures and 3D objects were compared to 2D and 3D chemical structural formulas to explore the strategies of mental rotation when identifying chemical structural formulas.

Mental rotation in the ERP study

The definition of mental rotation is that students need to rotate the stimuli mentally (Stieff, 2007). However, it is difficult to collect the data about mental rotation using questionnaires or interviews. Many previous studies have used different ERP research designs, such as the rotation of letters or pictures, to successfully investigate mental rotation (Heil, Rauch, & Hennighausen, 1998; Muthukumaraswamy, Johnson, & Hamm, 2003; Núñez-Peña & Aznar-Casanova, 2009; Peronnet & Farah, 1989; Rieĉanský & Jagla, 2008). Hence, this study adopted ERP technology to provide the physiology data to explain mental rotation. When the participants recognized or applied specific cognitive abilities such as memory or mental rotation to respond to the events, the corresponding electrical activities of the brain were induced (Liu, Huang, & Chou, 2010). The average of these activities was integrated in the form of specific ERP components (Coles & Rugg, 1995). The main set of components in this study was rotation-related negativity with latency between 400 and 800 ms (Heil et al., 1998; Heil & Rolke, 2002; Milivojevic, Johnson, Hamm, & Corballis, 2003; Núñez-Peña & Aznar-Casanova, 2009).

The negative peak that occurs between the latencies of 400 and 800 ms is called rotation-related negativity (Heil et al., 1998; Heil & Rolke, 2002; Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009) (Fig. 2). For example, when analyzing ERP data, if the mean amplitude of rotation-related negativity induced by rotating the 2D figures is to be the baseline, the mean amplitude of rotation-related negativity induced by rotating the 2D chemical structural formulas can be compared to the baseline. As previous studies have mentioned (Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009), if the mean amplitude induced by rotating 2D chemical structural formulas is smaller than the baseline, then the participants used less mental rotation in identifying the formulas than the figures. If the mean amplitude is similar to the baseline, then the participants used similar strategies of mental rotation to identify the 2D figures and the 2D formulas. Obviously, when they used more mental rotation in identifying 2D chemical structural formulas than 2D figures, the mean amplitude induced by rotating the formulas was larger than the baseline.

As Figure 2 shows, the larger mean amplitude of rotation-related negativity indicates that the participants used more mental rotation to complete the task than the baseline. In past studies (Heil et al., 1998; Heil & Rolke, 2002; Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009), the rotation-related negativity was always found in the central line of electrodes (FZ, CZ and PZ electrodes, as shown in Fig. 3). Therefore, in the current study, we analyzed the ERP data from the FZ, CZ and PZ electrodes.

This study used the number of correct responses to distinguish the students with different chemical structure learning abilities, while the mean amplitudes of rotation-related negativity in FZ, CZ and PZ were used to explore the influences of mental rotation on the identification of 2D and 3D chemical structural formulas and objects. Mental rotation is a complex cognitive process; here, this study used the ERP data to show the physiological evidence to interpret the influences of mental rotation on identifying chemical structural formulas. Moreover, this study also combined the test score and interview data to interpret how mental rotation strategies affect the identification of chemical structural formulas.

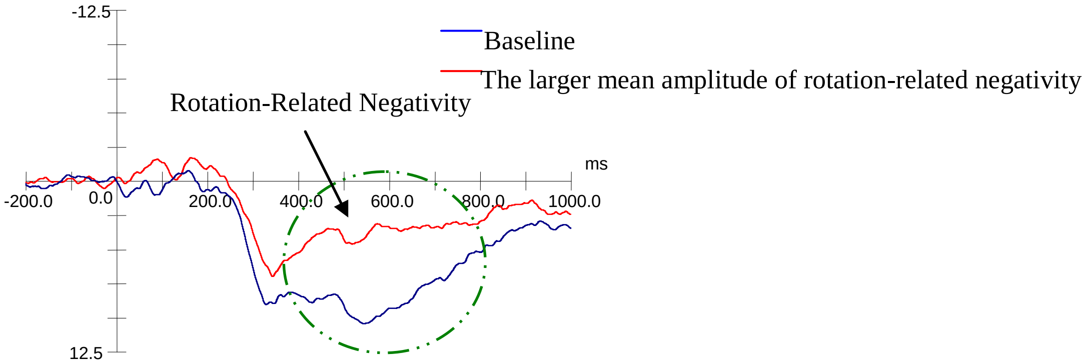


Figure 2. The rotation-related negativity in ERP analysis

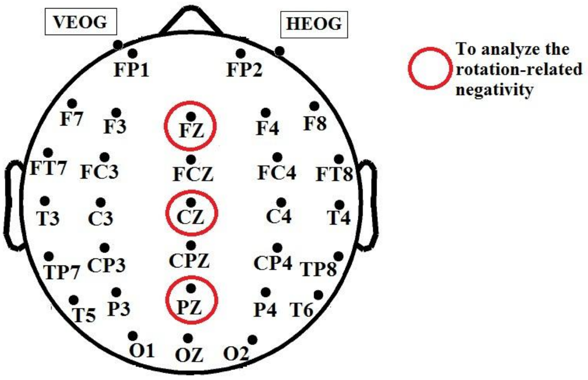


Figure 3. The locations of the FZ, CZ and PZ electrodes on a brain map.

Research Design

Participants and Instruments

This study was conducted at an urban university in Taiwan. Fifty university students majoring in chemistry (n = 50, 31 males, 19 females; mean age ± S.D. = 20.9 ± 2.0 years) participated in the study. Based on previous research (Chiu & Fu, 1993; Frailich et al., 2009), a questionnaire developed by the authors was administered to the participants. Chiu and Fu (1993) have developed a questionnaire to explore how Asian students solve stereochemistry problems and identify 2D and 3D chemical structural representations. Frailich et al. (2009) used integrated visualization tools to investigate students' strategies for learning chemical structural formulas and found that many important concepts of chemical bonding help students to learn these formulas. Based on these two studies, a Chemical Structure Conceptual Questionnaire (CSCQ) was developed in this study.

The CSCQ (perfect score = 100) consisted of 10 questions (perfect score for each question = 10). CSCQ example questions are shown in Table 1. CSCQ was used to gain an understanding of the learning performance of the students related to chemical structural formulas. The questionnaire was constructed using the Delphi method and was determined by reaching consensus. The expert panel was made up of two science educators, two science teachers, one chemist and two psychologists. All of the experts revised the CSCQ individually and exchanged opinions about revisions until they reached consensus. Then, the constructed questionnaire was tested on thirty university students majoring in chemistry to validate the content, obtaining a Cronbach's α value of .935.

Table 1. Examples of questions

Questions

1. Please complete the following questions:

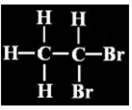
(a) Write down the chemical formula of methane. (3%)

(b) Draw the 2D chemical structure of methane. (3%)

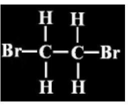
(c) Draw the 3D chemical structure of methane. (4%)

2. Look at these chemical structural formulas and complete the following questions:

(A)



(B)



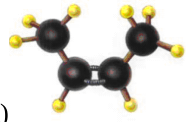
(a) Name the molecule of structure (A). (3%)

(b) Translate structure (A) into a 3D chemical structure. (3%)

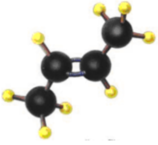
(c) Is chemical structure (A) the same as structure (B)? Why or why not? (4%)

3. Decide whether these two 3D chemical structural formulas are the same or not. Explain. (10%)

(A)



(B)



The CSCQ test lasted for 50 minutes, and the participants were not allowed to converse during the test. After the test, one science teacher graded the questionnaires, and the other confirmed the grading. Based on the scores of the questionnaire, students with the upper and lower 27% of total scores were grouped into the high score (HSG, n=9; mean age ± S.D. = 20.7 ± 2.7 years; mean score ± S.D. = 99.3

± 1.0) and low score (LSG, n=9; mean age ± S.D. = 20.4 ± 1.9 years; mean score ± S.D. = 67.6 ± 8.3) groups (Kelley, 1939). A prediction of the sample size was generated by GPower 3.1 Software. With power=0.90 and α=0.05, the sample size, that is 18 participants, was deemed appropriate (Sokel & Rolf, 1981). All participants were confirmed to be mentally healthy without a history of neurological or psychiatric disorders, and all gave voluntary consent to participate in the ERP experiments. This study conformed to The Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the ethics committee of the National Kaohsiung Normal University.

ERP Experiments

Based on the research questions, we designed four types of ERP experiments that included 2D geometric figures (2D figures), 2D chemical structural formulas, 3D geometric objects (3D objects) and 3D chemical structural formulas. The shapes of the 2D figures and 3D objects are the same as those of the 2D and 3D chemical structural formulas but do not display the chemical symbols (Fig. 4(a)). Each experiment included a short instructional statement and 62 trials (Fig. 4(b)). All experiments were repeated twice to determine the repeatability of the ERP signals. A pair of matched (n = 31) or unmatched (n = 31) figures was presented in each trial, and the participants needed to determine whether the pair was matched or not. The participants' responses were recorded by pressing different buttons automatically on the computer keyboard (matched: press ○; mismatched: press ×).

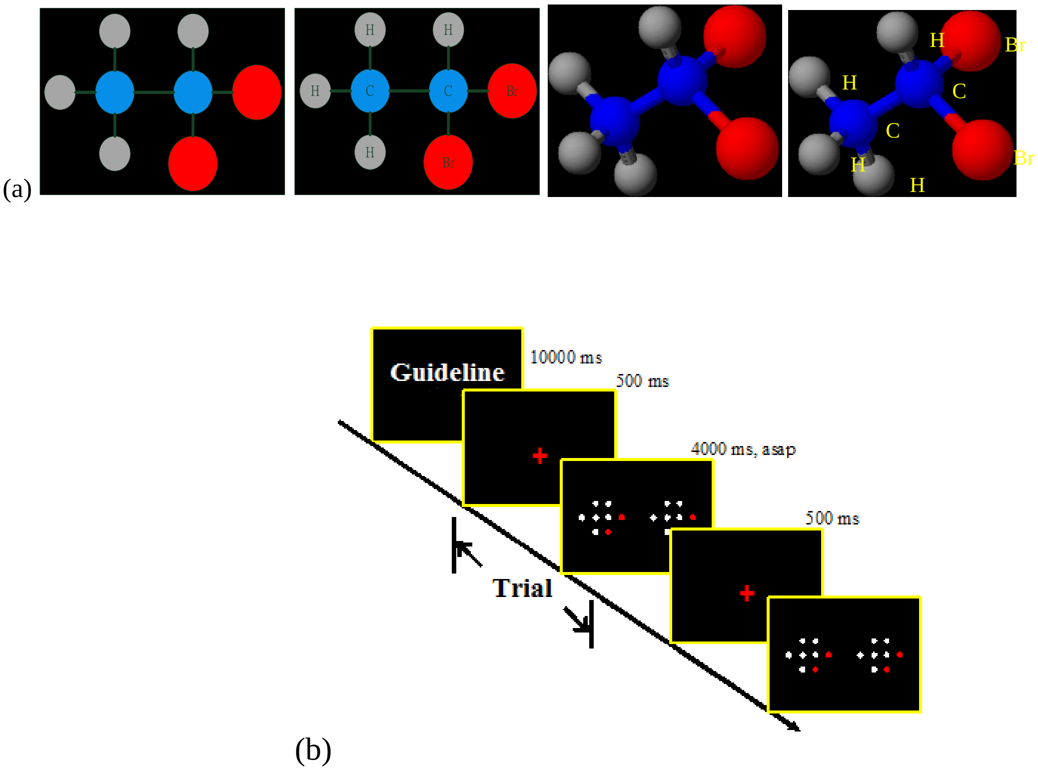


Figure 4 (a) Examples of the experimental tasks. (b) The meaning of "a trial" for ERP measurement.

An instructional message appeared for 10,000 ms on the screen before each experiment (Fig. 4(b)). Then, the sequence of every trial began with a red fixation point presented at the center of the screen, and remained in view for 100 ms. This point was used to help participants refocus after previous trials and pay attention to the center of the screen. The target slide of each trial was presented until the participants pressed the response button or, if there was no response, until 4,000 ms had passed.

Data Collection

The collected signals were identified using an electroencephalogram (EEG) in the ERP experiments as follows (Fig. 5).

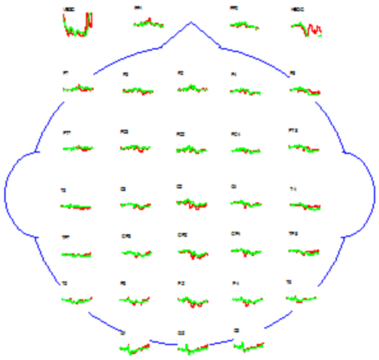


Fig. 5 An example of EEG signals

The EEG was amplified (band pass, 0.01-40 Hz) using SynAmps/SCAN 4.4 hardware and software (NeuroScan, Inc., Herndon, VA) and a commercial electro-cap (Electro-Cap International, Eaton, OH) with electrodes at 32 scalp locations based on the 10-20 International system. The noise signals were filtered out automatically. The electrode impedance was kept below 5 kΩ. The averaging epoch was 1024 ms, including 200 ms of pre-stimulus baseline. EEG channels were continuously digitized at a rate of 10,000 Hz using a SynAmp^{TM} amplifier. The signal was analog filtered (0.1-200 Hz), A/D converted with a sampling rate of 10,000 Hz, 14 bit precision and digitally filtered in the range 0.1-30 Hz. We recorded all participants' EEG signals when they were completing the experiments.

The scores and the ERP data were collected for analysis. Each correct response in every trial was scored as 1 point, and the best possible score was 62 points for one set of trials. Because every participant completed the trial twice, the highest possible score for the whole experiment was 124 points. For the ERP data, the mean amplitudes of the rotation-related negativity in FZ, CZ and PZ were collected (see Fig. 3). The extracted data were analyzed using a *t*-test (SPSS version 12.0).

Interviews

Semi-structured interviews were conducted to explore the strategies used for identifying chemical representations; the interviews were conducted after the students completed the ERP experiments. Each interview lasted 40 minutes and the response data were combined with the findings of the ERP data and the scores of the questionnaire.

Results and Discussion

The Behavioral Data

The results showed that there was no significant statistical difference between the high score group (HSG) and the low score group (LSG) students in their response scores of the ERP experiment for identifying 2D figures (Table 2). In contrast however, the scores of the HSG students were significantly higher than those of the LSG students for identifying 3D figures, 2D chemical structural formulas, and 3D chemical structural formulas. The results indicate that, in identifying geometric figures without content knowledge, the LSG students could identify 2D figures as well as the HSG students, but the HSG students performed better in identifying 3D objects, implying that the original difficulty for some students in learning chemical structural formulas might be due to their failure to identify 3D objects. These results are supported by previous studies (Gilbert, 2008; Gilbert & Treagust, 2009; Shubbar, 1990; Wu, Krajcik, & Soloway, 2001).

Table 2. *t*-test analysis of the *response* scores between and within the HSG and the LSG (n =18).

Variable	Experiment	Group	Mean ± S.D.	*t*	Cohen's *d*
Scores	2D	HSG	124.0 ± 0	1.5	0.707
		LSG	123.8 ± 0.4		
	2Dchem	HSG	118.9 ± 3.9	10.7***	5.059
		LSG	93.0 ± 6.1		
	3D	HSG	123.9 ± 0.3	2.4*	1.065
		LSG	122.6 ± 1.7		
	3Dchem	HSG	121.0 ± 2.8	11.3***	5.324
		LSG	98.1 ± 5.4		

* *P*<.05; ** *P*<.01; *** *P*<.001

Note: 2D: 2D figures; 3D: 3D figures; 2Dchem: 2D chemical structural formulas; 3Dchem: 3D chemical structural formulas.

Table 3 shows the response time (RT) data when the participants responded to the tasks in the ERP experiments. The results indicate that there was no statistically significant difference in the response times (RT) for identifying 2D figures, 3D objects and 3D chemical structural formulas between the HSG and the LSG groups, but the HSG students had a significantly longer RT for identifying 2D chemical structural formulas than the LSG students did (Table 3).

Table 3. The *t*-test analysis of response time (RT) between and within the HSG and the LSG (n = 18)

Variable	Experiment	Group	Mean ± S.D.	*t*	Cohen's *d*
RT	2D	HSG	1007.7 ± 297.3	-.573	-0.270
		LSG	1093.6 ± 337.6		
	2Dchem	HSG	1339.8 ± 370.2	2.52*	1.188
		LSG	1009.8 ± 131.5		
	3D	HSG	1031.6 ± 144.3	-.574	-0.268
		LSG	1083.8 ± 231.6		
	3Dchem	HSG	1228.2 ± 432.4	.790	0.372
		LSG	1073.1 ± 399.9		

* reach *P*<.05; ** reach *P*<.01; *** reach *P*<.001

Note: 2D: 2D figures; 3D: 3D objects; 2Dchem: 2D chemical structural formulas; 3Dchem: 3D chemical structural formulas.

Combining the results of Tables 2 and 3 indicates that the HSG and LSG students spent approximately the same amount of time identifying 2D figures, and performed equally well. However, although both groups spent a similar amount of time responding for the 3D figures and 3D chemical structural formulas, the HSG students got higher scores than the LSG students. The possible reason is that although the LSG students responded to the task quickly, they used the wrong or inappropriate strategies to identify the 3D figures and 3D chemical structural formulas.

Furthermore, the results show that the HSG students had a significantly longer RT for identifying 2D chemical structural formulas than the LSG students. Many studies have indicated that participants spend more time on this type of task when performing mental rotation (Cooper & Shepard, 1973; Heil & Rolke, 2002; Núñez-Peña & Aznar-Casanova, 2009). Hence, these results suggest that the HSG students might have used more mental rotation to rotate the 2D chemical structural formulas than the LSG students did.

However, the findings above could not clearly demonstrate the effects of mental rotation in identifying chemical structural formulas. Past neurophysiological studies have indicated that when humans respond to a task using mental rotation, the rotation-related negativity of ERP data could be induced. Hence this study adopted ERP data to investigate the influences of mental rotation on identifying 2D and 3D chemical structural formulas.

The Students Used the Least Mental Rotation for Identifying 2D Figures and the Most for Identifying 2D Chemical Structural Formulas

Numerous studies have reported that mental rotation tasks are always accompanied by rotation-related negativity potentials with latency between 400 and 800 ms for the FZ, CZ and PZ electrodes (Heil et al., 1998; Heil & Rolke, 2002; Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009). In this study, the mean amplitudes of rotation-related negativity were 0.318 ± 2.837 (mean ± S.D.) for identifying 2D figures, -1.796 ± 3.143 (mean ± S.D.) for identifying 3D objects, -6.593 ± 6.647 (mean ± S.D.) for identifying 2D chemical structural formulas, and -3.536 ± 4.252 (mean ± S.D.) for identifying 3D chemical structural formulas. The larger mean amplitude of rotation-related negativity indicates that the participants needed to use more mental rotation during the experiment (Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009). The results of the mean amplitudes of rotation-related negativity in this study show that the students used the least mental rotation in identifying 2D figures and the most in identifying 2D chemical structural formulas. However, in the ERP data, the HSG students showed different trends of rotation-related negativity potentials than the LSG students (Fig. 6).

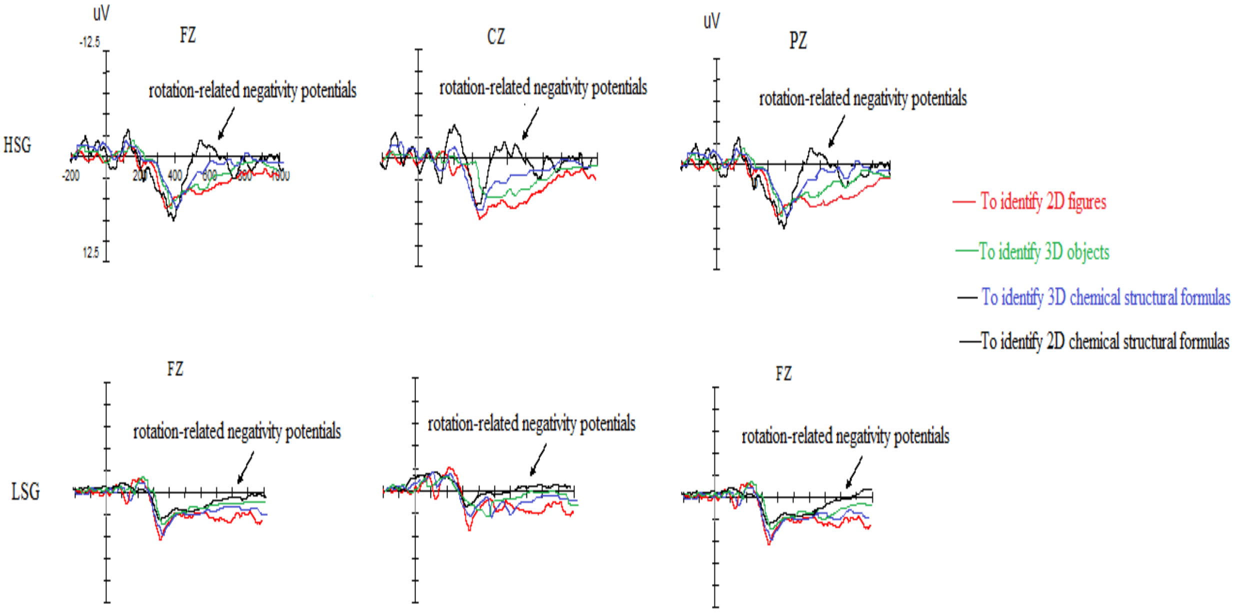


Figure 6. The different trends of rotation-related negativity potentials between the HSG and LSG students

For the HSG students, the amplitudes of rotation-related negativity potentials were the largest in identifying 2D chemical structural formulas and the smallest in identifying 2D figures. However, for the LSG students, the trends of rotation-related negativity potentials were not clear in the ERP data. Thus, a *t*-test was used to analyze the mean amplitudes of rotation-related negativity for the HSG and the LSG students (Table 4).

High Achieving Students Performed Mental Rotation More Frequently in Identifying 2D Chemical Structural Formulas than Low Achieving Students

The results presented in Table 4 show that there were no statistically significant differences between the HSG and the LSG students in identifying 2D figures, 3D objects and 3D chemical structural formulas. However, the HSG students had a larger mean amplitude of rotation-related negativity in identifying 2D chemical structural formulas than the LSG students (Table 4), especially for the FZ (frontal lobe of brain) and PZ (parietal lobe) electrodes. The results of the ERP data are supported by past studies that have indicated that the frontal and parietal cortexes are the most important brain areas in performing mental rotation (Cohen et al., 1996; Alivisatos & Petrides, 1997; Pegna et al., 1997; Milivojevic et al., 2003; Núñez-Peña & Aznar-Casanova, 2009).

Table 4. The differences in the mean amplitudes of rotation-related negativity between the HSG and the LSG students

Variable	Group	Mean ± S.D.	*t*	η^2
2D	HSG	-0.457 ± 2.654	-1.171	.079
	LSG	1.092 ± 2.952		
2Dchem	HSG	-10.145 ± 5.315	-2.634*	.302
	LSG	-3.041 ± 6.102		
3D	HSG	-1.861 ± 3.997	-0.085	.000
	LSG	-1.730 ± 2.238		
3Dchem	HSG	-5.122 ± 3.934	-1.662	.147
	LSG	-1.951 ± 4.158		

reach $P<.05$

The results in Table 4 demonstrate that the HSG and LSG students used similar mental rotation to identify 2D figures. When compared with Tables 2 and 3, the results indicate that both HSG and LSG students could respond for 2D figures correctly and quickly, and they performed less mental rotation to rotate 2D figures than for other tasks because it is the easiest task. This finding implies that the use of mental rotation to identify 2D figures is not the main cause of the differences between the HSG and LSG students in identifying chemical structural formulas.

Moreover, Table 4 shows that the mental rotation which the HSG and LSG students performed in identifying 3D figures had no statistical difference. The results indicate that the LSG students could identify 3D figures as quickly as the HSG students could. However, Table 2 shows that the HSG students got higher scores on identifying 3D figures than the LSG students. In other words, both the HSG and the LSG students used a similar amount of cognitive resources for mental rotation for identification of the 3D figures, but the HSG students had more correct responses. From the interview data, it was found that although both the HSG and the LSG students used similar mental rotation cognitive resources, the HSG students applied more strategies of mental rotation than the LSG students while identifying 3D figures. This may explain why the HSG students had better scores on identifying 3D figures.

> HSG1: You can focus on the central ball and rotate the specific ball in your mind to determine whether the figures are matched or unmatched.
>
> HSG5: I memorized the relative positions of the standard stimulus and compared the positions to the target stimulus. When the figures were rotated in my mind, the relative positions helped me to rotate correctly.
>
> LSG4: I think the whole figures were rotated in my mind. After the figures completed their rotation, I could find that the positions were different in these two 3D figures.
>
> LSG7: The 3D figures were rotated in my mind…whole figures were rotated in my imagination….

The interview data demonstrated that the HSG students used more strategies of mental rotation which included depth cues and relative positions to rotate the 3D figures, while the LSG students used a simple strategy to rotate the 3D figures. Hence, although the HSG and LSG students spent a similar amount of reaction time (RT) and mental rotation cognitive resource, the HSG students got higher scores on identifying the 3D figures.

Besides, there were no statistical differences in the rotation-related negativity potentials between the HSG and LSG students in identifying 3D chemical structural formulas. The interview data showed that the students applied similar strategies of mental rotation to identify 3D objects and 3D chemical structural formulas.

> HSG1: I can imagine the 3D chemical structural formulas in my mind and compare the other formulas by using mental rotation…just like rotating 3D figures.
>
> HSG5: You can rotate the chemical structural formulas in your mind…Yes, I rotated the 3D chemical structural formulas as 3D objects. You do not need to know what atoms are in the formulas because they are drawn with different colors.
>
> LSG2: I used the same strategies to discriminate these chemical structural formulas as I did for 3D objects. When this structure was rotated 180° on the X axis, these two structural formulas matched…I did not pay attention to the atoms because the atoms in the chemical structural formulas do not influence their rotation.

The interview data demonstrate that the students used similar strategies of mental rotation to rotate the 3D objects and 3D chemical structural formulas. This finding implies that if a student could rotate 3D objects well, he/she could also identify and rotate 3D chemical structural formulas well. Therefore, this study suggests that one of the difficulties of learning chemical structural formulas is students' inability to identify and rotate 3D objects.

The findings presented in Table 4 about 2D chemical structural formula identification imply that the HSG students used more mental rotation to identify 2D chemical structural formulas than the LSG students did. The interview data showed that the LSG 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, and they believe that the chemical bond is a real physical entity. The findings of past research indicating that some students believe that a chemical bond is a real physical entity and that they tend to use daily life experiences with real objects to rotate chemical structural formulas (Mathewson, 1999, Moè, 2009; Núñez-Peña & Aznar-Casanova, 2009; Stevens et al., 2010) were corroborated in this study.

HSG2: I determine the 2D chemical structural formulas and figures with different strategies……I need to transfer the 2D chemical structural formulas to 3D and rotate them, and then I can identify whether the formulas are the same or not.

HSG9: These two chemical structural formulas are the same because the single bond could rotate. In other words, the formulas are the same in spatial construction……No, there is a difference between identifying 2D figures and 2D chemical structures.

LSG2: I can image “Br” atoms as the specific balls, and imagine the single bond as the sticks in the 2D figures. Then I could rotate these 2D chemical structural formulas as I do for the 2D figures.

LSG3: Because the chemical bonds are the same as the sticks of objects, I think I can use the same strategies to identify 2D chemical structural formulas.

As Wu, Krajcik and Soloway (2001) and Boo (1998) mentioned, the LSG students did not understand the meaning of the 2D representation of chemical structural formulas, and failed to make the transformation between 2D and 3D 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 formulas are different.

Furthermore, Stieff (2007) reported that high-achieving students may use specific analytical strategies to transform the spatial relationships between different representations of chemical structural formulas without employing mental rotation. However, in our study, we combined a neurophysiological method, a questionnaire and interviews to find that the HSG students used mental rotation and specific analytical strategies together to identify the 2D chemical structural formulas.

Research Limitations

This study was subject to some limitations. Although the ERPs experiments could detect the brain activities of each person, due to the small sample size in this study these results should, perhaps, be interpreted with caution.

Conclusion

Three main conclusions can be drawn from this study: (1) the students used mental rotation most frequently in identifying 2D chemical structural formulas, and used mental rotation less frequently to rotate 2D figures; (2) the students used similar mental rotation strategies in identifying 3D objects and chemical structural formulas, but the high-achieving students performed better in identifying 3D objects and 3D chemical structural formulas because of the multiple and useful strategies of mental rotation; and (3) the high-achieving students performed mental rotation more often in identifying 2D chemical structural formulas than the low-achieving students did because the low-achieving students did not realize that the 2D chemical structural formulas were the projections of 3D chemical structural formulas. In other words, the low-achieving students used mental rotation which they used in identifying 2D figures to identify 2D chemical structural formulas. However, mental rotation is an inappropriate strategy in this case.

The results of this study illustrate that the high-achieving and low-achieving students spent a similar amount of time and got similar scores on identifying 2D figures, and they used similar mental rotation, inferred from the analysis of the ERP data from identifying 2D figures. Both the HSG and LSG students could respond to the 2D figures correctly and quickly, and they performed mental rotation less frequently to rotate 2D figures than for other tasks. This finding implies that the use of mental rotation for identifying 2D figures was not the main cause of the differences between the HSG and LSG students in identifying chemical structural formulas.

Besides, the results of this study found that the high-achieving and low-achieving students spent a similar amount of time and all used mental rotation to identify 3D figures. However, the high-achieving students got higher scores on identifying 3D figures than the low-achieving students did. Based on the qualitative and quantitative data, it is suggested that although both groups performed the similar cognitive resource of mental rotation to respond to 3D figure identification, the high-achieving students applied more strategies of mental rotation than the low-achieving students did. The high-achieving students used more strategies of mental rotation which included depth cues and relative positions to rotate the 3D figures, while the LSG students used a simple strategy which was to rotate the whole figure. It is suggested that when a student uses simple or inappropriate strategies to rotate 3D figures, he/she will not be able to identify and rotate 3D objects correctly.

Furthermore, the results of this study indicate that all of the students used similar mental rotation strategies to identify 3D figures and 3D chemical structural formulas. Therefore, if students cannot identify 3D figures well, they would feel that it is difficult to identify 3D chemical structural formulas. This finding is supported by previous studies (Gilbert, 2008; Shubbar, 1990; Wu, Krajcik, & Soloway, 2001; Wu & Shah, 2004). In our study, the results imply that the original difficulty for some students in identifying 3D chemical structural formulas might be their failure in identifying 3D objects. Although many previous studies have suggested that chemistry educators should demonstrate 3D reality or virtual models to improve students' understanding of 3D representation in chemical structural formulas (Stieff, 2007; Wu, Krajcik, & Soloway, 2001; Wu & Shah, 2004), this study further suggests that teachers should demonstrate the multiple rotation strategies of 3D models to promote students' performance of multiple strategies of mental rotation. It will help students develop the ability to identify 3D figures and 3D chemical structural formulas.

The results of this study also imply that high-achieving students use mental rotation more often to identify 2D chemical structures than low-achieving students. The interview data showed that the low-achieving students used similar strategies to identify 2D chemical structural formulas to those they used to identify 2D figures because they did not realize that the 2D formulas were in fact 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 formulas are different. Hence, as previous studies have suggested (Gilbert, 2008; Mathewson, 1999; Moè, 2009; Núñez-Peña & Aznar-Casanova, 2009; Seddon & Eniaiyeju, 1986; Shubbar, 1990; Stevens et al., 2010; Wu, Krajcik, & Soloway, 2001), assisting students to understand the translation between 2D and 3D chemical structural formulas by the use of virtual and reality models would facilitate the identification of 2D chemical structural formulas. Another reason why low-achieving students rotate the 2D chemical structural formulas as 2D figures is because they believe that a chemical bond is a real physical entity, and they do not understand the meaning of the 2D representation of chemical structural formulas (Boo, 1998). Therefore, they rotate 2D chemical structural formulas in the same way as 2D figures in daily life. These results should remind science teachers to pay more attention to students' misconceptions of "chemical bonds" in identifying the representations of 2D chemical structural formulas and 2D figures. Furthermore, science teachers must avoid only introducing the ball and stick models when teaching chemical structural formulas; they need to emphasize the translation between 2D and 3D chemical structural formulas through the use of multiple representations and analytical strategies.

Further, although some previous research has suggested that the use of mental rotation strategies decreases as one's expertise increases (Hegarty, 2004; Larkin et al., 1980; Stieff, 2007), this result was not supported in this study. The ERP data suggest that high-achieving students need to use more mental rotation to identify 2D chemical structural formulas than they do for the other tasks, and they use more mental rotation to identify 2D chemical structural formulas correctly than do low-achieving students. That is to say, although it is important to teach students to use analytical strategies to identify chemical structural formulas, the basic cognitive strategies of mental rotation should be taken into consideration when teachers design their teaching strategies and materials.

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