How Do the Prefrontal Lobes Mediate Scientific Reasoning and Conceptual Change in Adolescents ?

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청소년들에게서 전두엽연합령은 어떻게 과학적 추론 및 과학개념 변화의 수행을 매개하는가?

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ABSTRACT

청소년들의 과학적 추론이나 과학개념 변화에 영향을 미치는 변인들에 대한 교육학적 또는 심리학적 접근에서 수행된 연구들은 많지만, 아직 두뇌기능의 성숙적 측면에서 이들 변인에 대한 접근은 국내외적으로 거의 이루어지질 않았다. 이 연구는 청소년들의 과학적 추론 능력과 개념획득 능력이 그들의 전두엽연합령(prefrontal lobes)의 인지적 기능, 예를 들면 설계기능(planning function) 또는 억제기능(inhibiting function)의 성숙에 의해서 주로 매개된다는 가설을 테스트하였다. 이 가설을 테스트하기 위하여 한국의 중등학생들의 과학적 추론 능력, 수업을 통한 개념 변화 능력, 추론능력과 개념변화에 영향을 미치는 것으로 알려져 온 탈잠입능력과 작동기억용량, 그리고 설계능력과 억제능력을 조사하여 그들 사이의 상관성과 회귀계수를 알아보았다. 이 연구의 결과는 전두엽연합령의 설계능력과 억제능력이 과학적 추론 및 개념변화와 통계적으로 유의하게 관련되어 있음을 보여주었을 뿐만아니라, 더 나아가 과학적 추론과 개념변화에 이미 유의미한 인지변인으로 지지되어온 탈잠입능력과 작동기억용량보다 높은 지수로 관련되어 있음을 보여주었다. 이 연구는 또한 전두엽연합령의 인지적 기능들이 크게 활성과정(*representing process*)과 억제과정(*inhibiting process*)으로 수행되어짐을 보여주었고, 이들 두 인지과정은 과학적 추론과 개념변화과정은 물론 다른 인지활동에도 적용되어질 수 있음을 본 연구는 제시하고 있다.

Key words : 전두엽 연합령의 인지적 기능, 과학적 추론, 과학개념 변화, 활성과정, 억제과정, 설계기능, 억제기능, 과학학습.

Ⅰ. Introduction

Science educators have long tried to answer for the following classical questions : *Why do some adolescents perform well scientific reasoning tasks, whereas others do not? and why do some students more easily acquire scientific concepts during instruction, whereas others do not?* Beyond Piaget's explanations of maturation, experience, social transmission, and equilibration, studies in science education have shown that the following factors are significantly correlated with the adolescents poor performance on scientific reasoning tasks: maturation, working memory capacity, disembedding ability, and effec-

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tive teaching strategies (c.f., Lawson, 1985).

These explanations have broadened the overall understanding of scientific reasoning and conceptual change by characterizing various psychological and educational dimensions. However, there has been little progress made in pursuit of neurological level explanations of scientific reasoning and conceptual change. Notice all kinds of mental works are conducted by neural activities. Scientific reasoning and conceptual change also are important mental works which are required to be explained by neurological dimension. Therefore, an important task remains, namely, linking these psychological and educational phenomena with neurological activities.

Understanding the neurological mechanisms of higher cognitive processes has long been a concern of cognitive neuroscientists. Although details are lacking, substantial progress has been made in which prefrontal lobe damage causes substantial impairment of higher-cognitive activities, such as the association and regulation of complex actions (c.f., Harlow, 1868; Luria, 1980). The prefrontal lobes have a large amount of cortical space and rich connections with other brain areas (c.f., Fuster, 1989; Goldman-Rakic, 1987). Further, the prefrontal lobes do not mature until adolescence (Blinkov & Glezer, 1968; Yakoblev & Lecours, 1967), which nicely match with the onset of the formal stage of cognitive development (Thatcher, Walker, & Giudice, 1987). In addition, the prefrontal lobes are mainly responsible for higher cognitive functions has been supported by Luria (1980) and Stuss & Benson (1986). [See Kwon (1997) for a review in detail of anatomical, physiological, and clinical studies on the prefrontal lobes].

Because scientific reasoning is one of the higher cognitive processes and scientific reasoning skills are typically not achieved until adolescence, these findings have been suggestive of which the prefrontal lobes may be important in scientific reasoning. More recently, Hur, Lawson & Kwon (1997) have found that a prefrontal lobectomy patient can not solve successfully any task in a scientific reasoning test, which supports the claim that the prefrontal lobes are an important mediator of scientific reasoning. Nevertheless, the specific role that the prefrontal lobes play in scientific reasoning has not yet been detailed.

A long line of studies (Fuster, 1989; Luria, 1980; Milner, 1963; Stuss & Benson, 1986: Shallice, 1982) have found that prefrontal lobe damage leads to markedly poor performance on various tasks that require certain higher cognitive functions, such as working memory capacity, planning ability, inhibiting ability, and disembedding ability. [See Kwon (1997) for a review in detail of neurological studies that place working memory, planning, inhibiting, and disembedding functions of the prefrontal lobes]. Further, although working memory capacity and disembedding ability have been shown to significantly correlate with performance on formal reasoning tasks (c.f., Lawson, 1985), in contrast the limited planning and inhibiting abilities of the prefrontal lobes have been largely out of focused as mediators of scientific reasoning and conceptual acquisition.

Scientific reasoning and theoretical concept change involve a process of designing test procedure and predicting consequences. Designing test procedure presumably requires to plan a flow chart of future events, for example If . . . and . . . then . . . reasoning. Consequently, this activity includes the prediction of some consequences of future events. This process of designing test procedure and predicting consequences is nicely matched to the planning function of the prefrontal lobes. Therefore, planning ability may be an important mediator of performance on scientific reasoning tasks and the change of theoretical concepts during instruction. In addition, scientific reasoning and theoretical concept change also involves a process of suppressing incorrect hypotheses in light of contradictory evidence. The suppressing process presumably requires one to inhibit task-irrelevant information, but previously believed as the relevant, from the currently-activated information group. This process of suppressing task

-irrelevant information is nicely matched to the inhibiting function of the prefrontal lobes. Therefore, the inhibiting ability may also be another important mediator of scientific reasoning and theoretical concept acquisition during instruction.

Thus, the purpose of this study was to determine the extent to which function(s) of the prefrontal lobes based on neurological studies influences adolescents' performance on scientific reasoning tasks and their ability to change theoretical concepts during instruction. From this purpose and previous reviews, we may generate the following If . . . and . . . then . . . argument:

If . . . because planning and inhibiting functions of the prefrontal lobes are nicely matched to some procedures of scientific reasoning and theoretical concept change, those functions would be important mediators of scientific reasoning and theoretical concept change,

and . . . when we investigate correlation and regression coefficients between students' performance on tests of those prefrontal lobe functions, and their scientific reasoning skills and ability to acquire theoretical concepts,

then . . . we should see a significant correlation coefficients between students' performance on tests of prefrontal lobe functions, and their scientific reasoning skills and ability to acquire theoretical concepts.

Ⅱ. Method

1. Design

In the present study, prefrontal lobe functions were measured by the Tower of London Test (TOL) as a test of planning ability, the Wisconsin Card Sorting Test (WCST) as a test of inhibiting ability, the Group Embedded Figure Test (GEFT) as a test of disembedding ability and the Figural Intersection Test (FIT) as a test of working memory. Dependent variables were performance on a scientific reasoning test and pre- to post-test gains on a theoretical concept test during instruction.

Prior to instruction, students were individually administered tests of inhibiting ability (WCST) and planning ability (TOL). Written test of disembedding ability (GEFT) and working memory (FIT) were administered to students prior to instruction during their regularly-scheduled classes. Also prior to instruction, students were administered a written test of scientific reasoning ability and a test of air pressure concepts during their regularly-scheduled classes.

At the conclusion of pretesting, students were taught the series of 14 lessons, one lesson per week, over a 14 week period. All lessons were taught by the same instructor (author). At the conclusion of instruction, the test of air pressure concepts was re-administered to each class during their regularly-scheduled classes.

2. Subjects

Two hundred ten (210) volunteer students ranging from 13.1 to 17.1 years of age from two junior high schools and two senior high schools in Korea participated in the study. One junior and one senior high school were located in a city of approximately 100,000 people. The other junior and senior high school were located in a city of approximately two million people. Each student was enrolled in one of eight all male or all female eighth through eleventh grade science classes.

3. Instruments

1) Planning ability

Planning ability was assessed by the TOL. The TOL requires planning in terms of means-ends analysis to successively solve a set of increasingly difficult tasks (Krikorian, Bartok, & Gay, 1994; Kwon, 1997; Shallice, 1982). To solve each task, students must plan and execute a series of moves with success being defined in terms of task completion within a minimum number of moves.

Test materials (shown in Fig. 1) consisted of a board with three vertical wooden sticks of varying heights and three moveable balls. The balls, colored red, green, and blue, could be slid up and down the sticks. The first stick could hold all three balls. The second stick could hold two balls. And the third stick could hold just one ball. From the initial ball positions shown in Fig. 1, the student is asked to move one ball at a time from stick to stick, in a prescribed number of moves to achieve a certain predetermined goal (e.g., order the balls, green over blue over red on the long stick in five moves). The test requires students to plan a series of sub-goals as they must not only anticipate and visualize the end goal, but also each step to that goal must be mapped in the proper sequence.

Krikorian et al. (1994) developed a set of tasks appropriate for students in grades one through eight. Because the present study tested students in grades eight through eleven, the Krikorian et al. test was modified to include five additional tasks of increasing difficulty for a total of 12 tasks, two of which were practice. Each student was tested individually by one of five directions, on recording student responses, on checking time limits, and on giving feedback. The training session took about two hours. Inter reliability of the five interviewers was 0.95 for a sample of student responses.

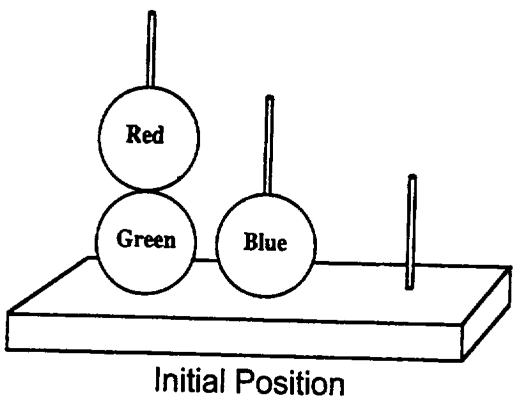

Fig. 1 The Tower of London Test

The easiest of the scored tasks required four moves and the most difficult required seven. Three trials were allowed for each task. Students were given one minute to reach the goal position per trial. Three points were awarded if the goal position was achieved in the prescribed number of moves and within the time limit on the first trial. Two points were awarded for a successful performance on the second trial. And one point was awarded for a successful performance on the third trial. If the student failed all three trials, a score of 0 was awarded. A student's total score was the sum of points earned on all 10 tasks. Thus, a maximum of 30 points was possible. In a pilot test of 30 9th-grade students, a Cronbach alpha of 0.61 was obtained.

2) Inhibiting ability

Inhibiting ability was measured by perseveration error on the WCST (Heaton, Chelune, Tally, Kay & Curtiss, 1993; Kwon, 1997). As shown in Fig. 2, The WCST consists of four stimulus cards and 128 response cards. The first stimulus card shows one red triangle. The second shows two green stars. The third shows three yellow crosses. And the fourth shows four blue circles. The 128 response cards have different shapes (crosses, circles, triangles, or stars), colors (red, yellow, blue, or green) and number of figures (one, two, three, or four).

At the beginning of the test, the student is given the 128 response cards and asked to match each

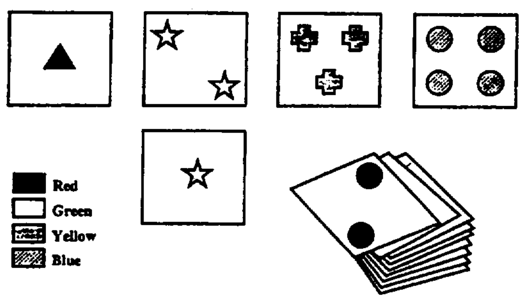

Fig. 2 The Wisconsin Card Sorting Test

card to one of the four stimulus cards. After each attempted match, the student is told whether the match is correct or incorrect, but not told the matching principle (i.e., match by color, match by shape, match by number). More specifically, the first matching principle was match by color. All other attempted matches were called incorrect. Once the student made ten consecutive correct color matches, the sorting principle was secretly shifted to shape. If the student continued to incorrectly match by color in spite of negative feedback from the interviewer, he/she is said to have committed a perseveration error (i.e., an incorrect response in card sorting in the face of negative feedback). After ten consecutive correct responses to shape, the principle was shifted to number and then back to color. This procedure continued until the student successfully completed six matching categories or until all 128 cards had been used.

Because this test was quire time consuming, five interviewers, trained by the researchers, were used to administer the test. Interviewer training included verbal explanations and practical examples on presenting the test directions, on recording student session lasted about two hours. Inter-rater reliability of five interviewers was 0.93 based on records of sample student responses.

The number of perseveration errors for each category were summed to obtain a total number for each student. Data analyses were then run using these numbers. However, note that inhibiting ability is inversely correlated with the number of perseveration errors. In other words, students that make fewer perseveration errors are assumed to have more inhibiting ability.

3) Disembedding ability

Disembedding ability was assessed by use of the GEFT (Witkin, Moore, Goodenough & Cox, 1977). The Korean version of the GEFT used in the present study consisted of 16 figures in each of two sections (Jeon & Jang, 1995). Students were given 10 minutes for each section. Ahn (1995) reported a Cronbach's alpha of 0.70 when the test was used with a sample of Korean secondary students similar to those in the present study.

4) Working memory

The FIT developed by Pascual-Leone & Smith (1969) has been used to assess students working memory (c.f., Pascual-Leone & Smith, 1969; see also Ahn, 1995). The version of the test used in the present study consists of 32 items. For each item, the student is asked to mark a point indicating the area of intersection of from two through eight overlapping figures. No time limit is given to complete the test. A maximum score of 32 points was possible. A Cronbach's alpha of 0.88 was obtained in a sample of Korean secondary school students similar to those of the present study (Ahn, 1995).

5) Scientific reasoning ability

A 14-item written test was used to assess scientific reasoning ability. The test is a modified version of Lawson's Classroom Test of Scientific Reasoning (Lawson, 1987). The modified test contained 8 of the original 12 items. The original items were based on Piagetian tasks and involve the identification and control of variables, and proportional, probabilistic, correlational and combinational reasoning. Two of the additional items on the modified test involve proportional and combinatorial reasoning and came from Lawson, Carlson, Sullivan, Wilcox & Wollman (1976). The four remain items came from Kwon (1997). Two of these involve water rise in an inverted cylinder after the cylinder had been placed over a burning candle sitting in water. The other two involve changes in the appearance of red onion cells when bathed in salt water. These four items require students to use hypothetico-deductive reasoning to reject hypotheses involving theoretical entities. For example, the burning-candle items ask students to propose an experiment to test and allow one to reject the hypothesis that water rises in th inverted cylinder because the carbon dioxide produced by the flame rapidly dissolves in the water.

All items required students to respond to a question or make a prediction in writing and to either explain how they obtained their answer, or in the case of quantitative problems, to show their calculations. Items were judge correct (a score of 1) if the correct answer plus an adequate explanation or set of calculation was present. Incorrect answers were scored 0. A Cronbach alpha reliability coefficient of 0.75 was obtained in a pilot study of 37 10th-grade students.

6) Understanding air pressure concepts

A test was constructed by the researcher to assess students' understanding of air pressure concepts. The test consists of six short-answer essay items concerning the causes of: 1. a milk shake traveling up in a straw when you "suck", 2. water rising in a cylinder inverted over a burning candle sitting in a pan of water, 3. a collapsing soda can submerged in cool water; 4. a peeled, hard-boiled egg entering a bottle that previously contained a burning piece of paper, 5. a rising hot air balloon and, 6. air entering your lungs. For example, Item 1 read: When drinking a milk shake with a straw, you can "suck" the milk shake into your mouth through the straw. How does "sucking" on the straw cause the milk shake to move up the straw? And Item 5 read: When you heat a hot-air balloon from below, th balloon rises. Explain why heating causes the balloon to rise.

Correct written responses were awarded 2 points each for a total of 12 possible points. Partially correct responses were awarded 1 point. Incorrect responses received 0 points. Content validity and item clarity were established through content-expert analysis prior to administration. A Cronbach's alpha reliability coefficient of 0.69 was obtained in a pilot study of 37 10th-grade students.

4. Instructional treatment

Instructional treatment consisted of 14 two-hour, inquiry-based lessons using the learning cycle method of instruction (Lawson, Abraham & Renner, 1989). Lesson 1 introduced students to the scientific method through use of examples of prior scientific research. Once the pattern of scientific research was introduced (i.e., *causal question → alternative hypotheses → planned tests → expected results → actual tests → actual results → conclusions*), students were given an opportunity to apply th pattern in the context of earthworm responses to various stimuli.

Lessons 2~4 provided students with an opportunity to apply th scientific method to generate and test hypotheses about why empty soda cans collapse when submerged in cool water. Following the test of several student-generated hypotheses, the instructor introduced relevant postulates of kinetic-molecular theory to explain the cause of greater air pressure outside the can, thus its collapse. Students were then challenged to apply the introduced concepts to predict and explain what will happen to air-filled balloons when cooled.

During lessons 5~7 students explored what happens when burning pieces of paper are dropped into bottles and then peeled hard boiled eggs are placed on the bottle openings. Based on their observations, students raised causal questions (e.g., What causes the eggs to move into th bottles?) and then generated and tested alternative hypotheses. The relevant postulates of kinetic-molecular theory were applied to explain the phenomenon. Students were then challenged to apply the theory to remove the eggs from the bottles and to explain what they did and why it worked.

Lesson 8~10 allowed students to explore what happens when an inverted cylinder is placed over a burning candle sitting upright in a pan of water. Students generated and tested several hypotheses in response to the question: What causes water to rise in the inverted cylinder? Again followed student hypothesis testing, relevant concepts of kinetic-molecular theory were applied to derive an explanation consistent with the students' observations.

During Lessons 11-12 students explored the causes liquids (e.g., milk shakes) moving up straws when students "sucked" on th straws. After again using air pressure concepts derived from kinetic-molecular theory to explain liquid movement, students were challenged to explain how syringes can be used to "draw" blood samples.

Lessons 13~14 challenged students to explore and explain how air passes into and out of one's lungs during breathing. Again relevant air pressure concepts were employed.

Ⅲ. Results

1. Predicting scientific reasoning ability

Table 1 shows the results of a stepwise multiple regression analysis used to determine which of the prefrontal lobe variables and age best predicts scientific reasoning ability. As shown, inhibiting ability, planning ability, disembedding ability, mental capacity and age significantly explained 56.1 % of the variance in scientific reasoning ability ($F_{5,204} = 30.63$, $p < 0.001$). Table 1 displays the R-Square increment of each predictor variable. Inhibiting ability explained the largest percentage of total variance (29.3 %). Next, planning ability explained 14.9 % of the variance. Age, disembedding ability, and mental capacity also explained significant amounts of variance (8.8%, 2.1% and 1.0 %, respectively).

Table 1 also shows standardized partial-regression coefficients of the prefrontal lobe variables. As you can see, the respective coefficients were 0.315, 0.338, 0.273, 0.137 and 0.112. Squaring these values gives the following estimates of the unique variance accounted for by each variable: 9.9%, 11.4%, 7.5%, 1.9% and 1.3%.

Table 1 Regression summary for prediction of scientific reasoning dependent variable: scientific reasoning N: 210 R: 0.749 R-square: 0.561

Predict	Increment of R-square	B	SE B	β
Plan. Abl.	0.149	0.349	0.053	0.338
Inhib. Abl.	0.293	0.110	0.018	0.315
Age	0.088	0.073	0.013	0.273
Disem. Abl.	0.021	0.078	0.028	0.137
Work. Memo.	0.010	0.100	0.046	0.112

Note. Plan. Abl.= planning ability; Inhib. Abl.= inhibiting ability; Disem. Abl.= disembedding ability; Work. Memo.= working memory; N= number of subjects; R= regression coefficient; B= partial-regression coefficient; SE B= standard error of partial-regression coefficient; β= standardized partial-regression coefficient.

2. Predicting concept gains

Table 2 shows the results of a stepwise multiple regression analysis used to determine which of the prefrontal lobe functions, age, reasoning ability, and concept pretest scores (prior knowledge) were significant predictors of concept gains. As shown, inhibiting ability, reasoning ability, concept pretest, age and planning ability significantly explained 42.9 % of the variance in concept gains ($F_{5,204} = 52.20$, $p<0.001$). Specifically, inhibiting ability was the best single predictor explaining 28.1% of the variance. Reasoning ability, concept pretest, age and planning ability explained 6.9%, 5.4%, 1.4% and 1.1% of the respective variance.

Table 2 Regression summary for prediction of pre- to post-test gains dependent variable: concept gains N: 210 R: 0.655 R-square: 0.429

Predict	Increment of R-square	B	SE B	β
Sci. Rea.	0.069	0.276	0.017	0.369
Inhib. Abl.	0.281	0.090	0.063	0.343
Con. Pre.	0.054	−0.344	0.073	−0.307
Age	0.014	0.030	0.012	0.146
Plan. Abl.	0.011	0.098	0.049	0.127

Note. Sci. Rea.= scientific reasoning ability; Con. Pre.= pretest performance on concept test.

Table 2 also shows that the standardized partial-regression coefficients for the respective predictor variables were 0.343, 0.369, −0.307, 0.146 and 0.127, respectively. Note that the concept pretest coefficient was negative indicating that prior knowledge had a negative effect on concept gains. With the effect of other predictor variables partialed out, the predictor variables explained 11.8%, 13.6%, 2.1% and 1.6 % of the respective variance in concept gain scores.

3. Intercorrelations among study variables

Table 3 shows Pearson product-moment correlation coefficients among the study variables. As you can see, all study variables correlated significantly with scientific reasoning ability with coefficients ranging from 0.36 for disembedding ability to 0.73 for the concepts posttest. The correlation of scientific reasoning ability with concept pretest was 0.57, with concept gains was 0.51, and with concept posttest was 0.73.

The four prefrontal lobe functions showed positive and significant correlations with scientific reasoning ability, with concept gains, and with concept posttest scores. Inhibiting and planning ability showed the highest correlations with reasoning ability (0.54); while inhibiting ability showed the highest correlation with concept gains (0.53) and with concept posttest scores (0.55). Intercorrelations among the prefrontal lobe functions were low to moderate (0.20, NS to 0.35, $p<0.01$).

4. Common components of study variables

Table 4 shows the results of a principal components analysis of all study variables. The analysis was conducted with varimax rotation extracting eigenvalues greater than one. As you can see, two principal components were extrac-

Table 4 Principal component analysis of study variables

Variables	Component 1 (29.5%)	Component 2 (27.2%)
Plan. Abl.	0.48	0.39
Inhib. Abl.	0.22	0.75
Disem. Abl.	0.29	0.30
Work. Memo.	0.51	0.31
Age	0.50	0.17
Sci. Rea.	0.70	0.53
Con. Pre	0.92	0.04
Con. Post	0.66	0.63
Con. Gain	0.10	0.92

Note. ( ) = percent of total variance explained by each component.

Table 3 Correlation coefficients among study variables

	Plan. Abl.	Inhib. Abl.	Diem. Abl.	Work. Memo.	Age	Sci. Rea.	Con. Pre	Con. Post	Con. Gain
Plan. Abl.	1.00								
Inhib. Abl.	0.31**	1.00							
Disem. Abl.	0.26**	0.20	1.00						
Work. Memo.	0.30**	0.35**	0.24*	1.00					
Age	0.11	0.20	0.17	0.19	1.00				
Sci. Rea.	0.54**	0.54**	0.36**	0.41**	0.42**	1.00			
Con. Pre	0.35**	0.26**	0.14	0.36**	0.30**	0.57**	1.00		
Con. Post	0.47**	0.55**	0.24*	0.44**	0.40**	0.73**	0.70**	1.00	
Con. Gain	0.34**	0.53**	0.20	0.29**	0.29**	0.51**	0.08	0.77**	1.00

*Note.** $p<0.05$, ** $p<0.01$. Con. Post= posttest performance on concept test. Con. Gain= pre- to posttest gains in concept test.

ted accounting for 29.5% and 27.2% of the variance respectively. Inhibiting ability loaded most strongly on component 2 (0.75), while the other prefrontal lobe functions loaded moderately on both components. Age loaded primarily on component 1 (0.50). Scientific reasoning ability loaded moderately on both components (0.70 on component 1 and 0.53 on component 2). Concept pretest loaded heavily on component 1 (0.92), while concept gains loaded more strongly on component 2 (0.92). Concept posttest loaded moderately on both components (0.66 on component 1 and 0.63 on component 2).

Ⅳ. Discussion

1. Scientific reasoning and conceptual change

Using regression analysis, the present study showed that subjects' performance on the tests of prefrontal lobe functions significantly predicted their performance on scientific reasoning tasks (see Table 1). Specifically, inhibiting and planning abilities showed the highest predictive values (i.e., increments of R-square and standardized partial-regression coefficients) for scientific reasoning, which conformed the prediction that subjects' performance on tests of planning and inhibiting abilities would show significant regression-coefficient for scientific reasoning. Also, the results that disembedding ability and working memory showed a statistically significant regression-coefficients for scientific reasoning add to the growing list of studies that have found those functions to be important predictors of scientific reasoning. Further, performance on tests of planning and inhibiting abilities showed higher value in regression analysis between scientific reasoning and predictive variables than working memory and disembedding ability. Because working memory and disembedding ability have been supported as strong predictors of scientific reasoning (c.f., Lawson, 1985), the results that planning and inhibiting abilities showed higher regression coefficients for scientific reasoning than working memory and disembedding conform the prediction that planning and inhibiting abilities are strong predictor of reasoning skills. Therefore, the hypothesis that scientific reasoning is in part dependent upon inhibiting and planning functions of the prefrontal lobes is supported.

The finding that the functional maturation of the brain (i.e., the prefrontal lobes) plays a role in the development of reasoning ability is consistent with Piagetian theory. Piaget has long argued that the development of reasoning is a product of both maturation and experience. For example, with regard to the development of formal operational structures, Inhelder and Piaget (1958) had this to say: "...this structure formation depends on three principal factors: maturation of the nervous system, experience acquired in interaction with the physical environment, and the influence of the social milieu." (p.243). Even Piaget argued that the maturation of the nervous system mediates scientific reasoning skills, the present study elaborates the notion into specific areas and functions of the brain beyond the Piagetian argument.

Results of the multiple regression analyses shown in Tables 5 and 6 indicate that concept gains are best predicted by inhibiting ability and by reasoning ability, while concept posttest scores are best predicted by reasoning ability and significantly predicted by inhibiting and planning abilities. Notice the results showed that learning capacity as evidenced by concept gains was mainly influenced by inhibiting function of the prefrontal lobes. Further, performance on tests of inhibiting and planning abilities showed similar value in regression analysis between concept gains and predictive variables to scientific reasoning ability. Because scientific reasoning ability have been supported as a strong predictor of theoretical concept change (c.f., Baker, 1994), the results that inhibiting and planning abilities showed similar regression coefficients for theoretical concept change to scientific reasoning ability conform the prediction that inhibiting and planning abilities are strongictor of theoretical concept change. Therefore, the hypothesis that theoretical concept acquisition is in part dependent upon the functional maturation of the prefrontal lobe is supported. Also, the results add to the growing list of studies that have found reasoning ability to be a strong predictor of concept acquisition. More will be said next section about how prefrontal lobe functions may influence reasoning ability and conceptual change.

In addition, the fact that prior knowledge had a negative impact on concept gains (Table 2) is inconsistent with the often posited view that the primary determiner of what students learn is what they already know in terms domain-specific concepts (e.g., Novak, 1977). However, the finding is consistent with the results reported by Johnson and Lawson (1998) in which reasoning ability, but not prior biology knowledge, predicted achievement in a college biology course.

2. Further consideration of prefrontal lobe functions and cognitive processes

The generally positive intercorrelations among the study variables shown in Table 3, as well as the results of the principal components analysis shown in Table 8, suggest that the study variables can be reduced to a smaller number of cognitive parameters. Note in Table 4 that among the prefrontal lobe functions, inhibiting ability loaded primarily on component 2 while planning ability and working memory loaded more strongly on component 1. Disembedding ability loaded moderately on both components. Thus, it appears that the prefrontal lobes functions may be involved in executing two primary functions - an "*inhibiting*" function related to performance on the Wisconsin Card Sorting Test, and one that we might call a "*representing*" function related to performance on the Tower of London and Figural Intersection Tests. Performance on the GEFT appears to be related to both components, thus would seem to involve both *inhibiting* and *representing* functions.

As mentioned, perseveration errors on the WCST involve the use of a sorting rule after it is no longer appropriate. Thus, such errors represent the inefficient deactivation of the task-irrelevant information that was initially, but is no longer, task relevant. In this sense, inhibiting ability refers to an active process that suppresses task-irrelevant information by removing it from the currently-active information group. In contrast, performance on the TOL can be thought of as requiring the internal representation of future events to attain a goal through a series of intermediate steps. Similarly, performance on the FIT and GEFT requires the activation of internal representations to locate the intersection of several overlapping figures and to identify the simple figures concealed in a complex ones. Thus, planning ability, working memory and disembedding ability may be cognitively linked by their common need to internally represent a set of task-relevant information units. Viewed in this way, successful mental processing involves the inhibition of task-irrelevant information and the representation of task-relevant information.

Notice in Table 4 that scientific reasoning ability loaded moderately on both components. This result suggests that effective scientific reasoning involves both the inhibition of task-irrelevant information as well as the representation of task-relevant information. For example, in the well-known pouring water task (Suarez & Rhonheimer, 1974) students are shown a wide and a narrow cylinder and asked to predict how high 6 units of water in the wide cylinder will rise when poured into the narrow cylinder. This prediction is called for after students have seen that 4 units of water in the wide cylinder rise to 6 units in the narrow. Thus, to correctly solve the task, students must suppress the task-irrelevant information that the water rose two more units before, to prevent them from incorrectly predicting that it will rise two more units again-to the 8th mark. If they can inhibit this task-irrelevant information, they are then free to "represent" the task as one involving a proportional relationship (i.e., 4 is to 6 as 6 is to 9), to correctly predict that the water will rise to the 9th mark.

In addition, concept pretest scores loaded heavily on the representing component (component 1). Concept posttest scores loaded moderately on both the representing and inhibiting component (component 2). And concept gains loaded heavily on the inhibiting component. This final result suggests that students who made substantial gains did so primarily because they were able to inhibit task-irrelevant information. Let's turn to an analysis of the actual instruction to see if we can find evidence of the need for inhibiting ability to make conceptual progress.

With respect to air-pressure concepts, one does not have to go far to identify two intuitively-derived "misconceptions" that need to be inhibited to successfully conceptualize the causes of air-pressure changes. The first is the "suction" misconception. When one "sucks" on things such as straws, it intuitively seems as though one is pulling air /liquid up through the straw. Nevertheless, kinetic-molecular theory tells us that no such pulling or sucking force exists. And second, even though we certainly can not directly sense the tremendous weight of air pushing down on our bodies, we nevertheless "know" (again via kinetic-molecular theory) that air has weight and can create a considerable downward force when not opposed by an equal upward force.

Viewed in this way, the key instructional question becomes one of how to overcome these sorts of misconceptions. Let's focus on lessons 8~10, which dealt with the burning candle in the pan of water experiment. This is a particularly interesting experiment because it causes many students to invoke still another misconception, namely the misconception that combustion "eats" or "consumes" oxygen.

When students place an inverted cylinder over a birthday candle sitting in a pan of water, they see that the candle quickly goes out and the water rushes up into the cylinder. Thus, an interesting question is raised. Namely, why did the water rise in the cylinder? The most common student-generated hypothesis is that the candle burned up the oxygen and this "lack-of-oxygen" sucked the water up. Notice that this hypothesis contains at least two major misconceptions (i.e., combustion creates a partial vacuum and partial vacuums pull /suck things up).

Instruction was designed to have students generate and test this hypothesis along with several others (e.g., the flame increases the temperature of the surrounding air, thus drives some away to eventually lower the internal air pressure; so once the candle goes out, the remaining air cools and contracts to lower the internal air pressure).

Notice that testing these alternative hypotheses requires use of some rather sophisticated scientific reasoning. For example, when we pit the oxygen-consumption hypothesis against the air-expansion-and-contraction hypothesis, we get the following argument:

If...water is sucked up because oxygen is consumed creating a partial vacuum (oxygen-consumption hypothesis),

and...the height that water rises with one, two, three, or more candles is measured (all other things being equal),

then...the height of water rise should be the same regardless of the number of burning candles. This result is expected presumably because there is only so much oxygen in the cylinder. So more candles will burn up the available oxygen faster; but they will not burn up more oxygen. Hence, the water level should rise the same.

On the other hand,

If...the air-expansion-and-contraction hypothesis is correct,

then...more candles should cause more water to rise - presumably because more candles will heat more air, thus more will escape, which in turn will be replaced by more water when the remaining air cools and contracts. (Note: One candle burning over a longer time period releases as much energy as three candles burning a shorter time, but one candle will presumably not raise the cylinder's air temperature as much because energy is dissipated rather quickly).

Once these hypothetico-deductive arguments have been generated, students carry out the experiment and report results, which are that the water level is dramatically affected by the number of candles (the more candles the higher the water level). Therefore, the oxygen-consumption hypothesis is contradicted and the air-expansion-and-contraction hypothesis is supported. Also the water rises after the candles go out, not while they are burning - another observation that contradicts the oxygen -consumption hypothesis and supports the air-expansion-and-contraction hypothesis.

So what does it take to get students to reject their incorrect hypothesis (one complete with misconceptions) and accept the scientifically correct hypothesis? Based on this analysis, it would seem that students have·to initially suspend (i.e., inhibit) their initial incorrect beliefs. In other words, they have to at least be willing to admit that their initial ideas might be wrong and be willing to test them. Students must then mentally represent some rather abstract /imaginary entities (i.e., moving and colliding molecules) and then understand (assimilate) arguments of the *if... and... then... but... therefore...* form. In other words, they have to inhibit task-irrelevant information, represent task-relevant information and reason scientifically. Small wonder that inhibiting ability, representing ability, and scientific reasoning ability are excellent predictors of conceptual gains and posttest scores.

V. Conclusions and Educational Implications

In conclusion, the present results provide support for the hypothesis that representing, mainly planning and working memory, and inhibiting functions of the prefrontal lobes play an important role in scientific reasoning and conceptual change in adolescence. In short, functional maturation of the prefrontal lobes during early adolescence appears to be linked to students' abilities to inhibit task-irrelevant information and mentally represent task-relevant information, which along with both physical and social experience influences scientific reasoning ability and students' ability to reject intuitively-derived scientific misconceptions and accept scientific, but counter-intuitive, conceptions. This conclusion is similar to that drawn by Lawson(1993) in which an earlier brain growth spurt at age seven was linked to students' ability to acquire descriptive concepts.

This study holds several implications for instruction designed to improve scientific reasoning and teach theoretical concepts. An important contribution of the present study involves finding significant roles of inhibiting and representing ability in developing scientific reasoning skills and learning theoretical concepts. At a basic level, learning may be described as acquiring knowledge about which information is relevant and which is not relevant for a given set of circumstances. In this way, learning involves representing relevant information and suppressing irrelevant information. Interestingly, the inhibiting process has been downplayed relative to the representing process (c.f., Dempster, 1991; Harnishfeger, 1995). But the inhibiting function has been found to be involved in a central function of the prefrontal lobes (c.f., Milner, 1963; see also Fuster, 1989; Luria, 1980) and does not fully mature until late adolescence (c.f., Heaton et al., 1993). Therefore, one central suggestion for learning scientific reasoning skills and theoretical concepts is that teaching should be concerned with learners ability to inhibit irrelevant information.

Given that many students appear to not have a sufficient operation of inhibiting and representing abilities for developing more advanced reasoning skills and acquiring theoretical concepts, they need effective teaching strategies to assist them in inhibiting irrelevant information and representing relevant information. How, then, can teaching assist? In agreement with Chamberlin (1898), Lawson

& Lawson (1979) and Platt (1964), it seems clear that when hypotheses are generated, students should be encouraged to design test procedures. And when the proposed hypotheses lead to predictions that are contradicted, students should be encouraged to reject and discard their hypotheses.

A clear pattern of instruction to assist the inhibiting and representing processes has been given by researchers (c.f., Kwon, 1996; Lawson, Drake, Johnson, Kwon & Scarpone, in press). The steps are taught as follows: 1) Raise questions (for example, what causes water to rise in a cylinder?). 2) Ask for student ideas and list them. 3) Design procedures to test the proposed ideas. 4) Predict consequences 5) Conduct experiments and collect the actual data/results. 6) Compare the actual results to the predicted results. 7) Draw conclusions including the hypotheses that should be rejected and discarded. 8) Move on to other questions and repeat the procedure. Such a teaching approach satisfies both requirements of assisting in the representing of task-relevant information and in inhibiting task-irrelevant information. Therefore, it presumably allows one to strengthen both abilities.

Abstract

The present study tested the hypothesis that adolescents' performance on scientific reasoning tasks and their ability to change theoretical concepts during instruction are mediated by prefrontal-cognitive functions, such as planning and inhibiting. Subjects sampled from four Korean secondary schools were administered a test of scientific reasoning ability and tests of the prefrontal lobe functions. A series of lessons on theoretical concepts was also administered. Subjects' performance on the test of scientific reasoning and pre- to posttest gains in the concept test were used as dependent variables. This study found that students' planning and inhibiting abilities were highly correlated with and they significantly predicted their scientific reasoning ability and conceptual gains. Further, principal component analysis showed prefrontal lobe functions were categorized into two main components. Component 1, which was loaded by planning and working memory functions, was termed as the *representing* process. Component 2, which was loaded primarily by the inhibiting functions, was termed as the *inhibiting* process. Scientific reasoning and conceptual change were also linked to these two components, indicating that these cognitive processes are mediated by both representing and inhibiting processes.

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