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Do the brain networks of scientists account for their superiority in hypothesis-generating?

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Where do scientists' superior abilities originate from when generating a creative idea? What different brain functions are activated between scientists and i) general academic high school students and ii) science high school students when generating a biological hypothesis? To reveal brain level explanations for these questions, this paper investigated neural connectivity differences between general and science high school students and biologists during hypothesis-generating and hypothesis-understanding using fMRI. Researchers designed two sets of task paradigm on biological phenomena, one for hypothesis-generating and the other for hypothesis-understanding. Thirty-six healthy participants (twelve participants per group) were given hypothesis generating and understanding tasks. Results showed strong interconnections of functional connectivity in the biologist group, which is acknowledged as possessing superior hypothesis generation skills. The group was also found to have significant functional connectivity between the frontal cortex and the mesolimbic system, which has been documented as the fronto-striatal pathway. Moreover, the biologist group recorded higher interconnections in other functional connectivities known to be associated with hypothesis-generating. Taken together, it can be concluded that the hypothesis-generating skill gap between groups resulted from activation of particular regions as well as interconnections of functional connectivity related to network fluidity. Specially, the biologists' hypothesis-generating superior skill resulted from highly strengthened interconnections of functional connectivity.

Keywords: High school student; Biologist; Functional brain connectivity; Hypothesis-generating; Functional magnetic resonance imaging (fMRI)

Introduction

How do biologists generate hypotheses from actual complex biological phenomena? Where do their excellent hypothesis-generating abilities stem from? In terms of the hypothesis-generating process as it relates to complex natural phenomena, what difference exists among the following three groups – general high school students, science high school students, and biologists? For several years, psychologists, scientists, and teachers have been seeking answers to these questions because the answers would make it possible to educate general high school students to the level of a scientist (Kwon & Lee, 2007; Lawson, 2002; Jin, Kwon, Jeong, Kwon, & Shin, 2006a; Thargard, 1998). There have been many studies on the hypothesis-generating skills of scientists and gifted high school science students; yet, most of these studies dealt only with observable

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results (Kwon & Lee, 2007).

Thus far only a few studies, in various fields, have discussed the idea that neural substrates, while maintaining the same cognitive function or sensory-motor skill, can differ according to group type (Chen et al., 2006; Kawashima et al., 2004; Kirk, Skov, Christensen, & Nygaard., 2008; Lotze, Scheler, Tan, Braun, & Birbaumer, 2003; Percio et al., 2008; Scanderbeg et al., 2005; Wright, Matlen, Baym, Ferrer, & Bunge, 2008). These researches have all concluded that differences in brain activation contribute to differences in ability. Despite these conclusions, however, no study has explored group differences as they relate to hypothesis-generating and hypothesis-understanding. Furthermore, all previous studies have focused solely on particular regional activations.

Some recent studies have proven that an individual's biological hypothesis-generating skill can generate difference in group brain activation. The hypothesis-generating research of Lee, Lee, Jeong, & Kwon (2008) through fMRI also provided evidence of differences in the levels of brain activation regions and signal intensity among scholars (biologist vs. humanist).

A hypothesis is a high-order inferential process that requires complex subordinate cognitive format (Lawson, 1995). From a cognitive psychological perspective, hypothesis generation has been regarded as a causal inference (Kwon, Jeong, & Park, 2006; Lawson; 1995), and it has been suggested that making causality is clearly rooted in perceptual experience (Hanson, 1958). However, it goes beyond perception in inferring relationships. It includes the retrieval and activation of information within long-term memory (LTM), the appropriate selection of relevant semantic information, the short-term retention of information within working memory, and the encoding of information into people's LTM (Kuperberg, Lakshmanan, Caplan, & Holcomb, 2006). Therefore, an intimate connection among all brain regions is necessary for successful hypothesis generation. In other words, the hypothesis-generating skill cannot be fully understood by only examining differences between brain activation regions or differences in the levels of particular regions. An alternative explanation can be found in functional connectivity. This concept can explain intensity among brain regions and is often used by scientists who research the human brain in terms of network units.

It was once reported by Koshino et al. (2005) that difference in cognitive functions between a normal group and a high-functioning autism group is related to differences in functional connectivity. In a recent study on biological hypotheses by Jin, Kwon, Jeong, Kwon, and Shin (2006a), mutual information analysis through EEG readings revealed relatively higher information transmission amongst gifted-children. They also concluded that gifted-children more efficiently distribute cognitive resources needed to cope with hypothesis-generating. The experiment, however, used a 16-channel EEG, which due to its low space resolution, could not fully reveal the exact region or network structure employed by the gifted-children. The experiment also did not reflect the hypothesis-understanding process, for it was limited to the hypothesis-generating process.

Therefore, this study hypothesized that differences in hypothesis-generating skills among groups could be due to differences in brain functional connectivity. If this hypothesis is proven correct, it would suggest that functional connectivity in the brain is controlled by differences in hypothesis-generating ability.

The purpose of this study is to test this hypothesis as it relates to differences in neural connectivity between general high school students, science high school students, and biologists during hypothesis-generating and hypothesis-understanding using fMRI. Not only was the hypothesis-generating process, the core of scientific research, tested but the hypothesis-understanding process was also tested in this study. These two processes for the three groups were compared in terms of different standards such as region, signal intensity, and network.

Methodology

Participants

Thirty-six male right-handed, healthy volunteers participated in the fMRI experiment. All participants were separated into three distinct groups (12 participants per group). The first group consisted of general high school students (mean age 16.79; range 16 - 17; all 10th graders), and the second group was comprised of science high school students (mean age 16.86; range 16 - 17; all 10th graders). The last group consisted of biologists (mean age 39.08; range 36-42) all of whom had doctorate degrees (Ph. D) in biology and were involved in scientific research or employed at a university (e.g. full-time researcher or professor). Also, all the biologists were screened to ensure they were currently involved in research and were publishing and/or planned to publish their results.

All participants had normal or corrected-to-normal visual acuity, no history of neurological, psychiatric or major medical illness, and were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). Each participant and their parents (for the student groups) gave informed consent prior to their inclusion in the experiment in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of Korea National University of Education (KNUE).

Behavioral data acquisition and analysis

Both behavioral and fMRI data were analyzed in this study to investigate differences in brain functions connected to hypothesis-generating and hypothesis-understanding between scientists and high school students, both general and science. Two types of tasks investigated the behavioral patterns of participants in this study. The first measured response accuracy using a computer mouse and the second investigated scientific hypothesis generation skills using a HQ (hypothesis explanation quotient) questionnaire (Lee, 2009). Participants' scientific hypothesis generation skill was tested twice before fMRI scanning sessions.

To quantitatively measure scientific hypothesis generation skill on biological phenomenon, this study employed Kwon, Lee, and Jeong (2007)'s HQ equation: $\mathrm{HQ} = \Sigma\{\mathrm{LE}_n \times \Sigma(\mathrm{DL}_n \times \mathrm{TH}_n)\}$ (HQ: hypothesis explanation quotient, LE: levels of *explican*, TH: types of hypotheses, DL: *explican*'s degree of likeness, n: n^{th} *explican*). Detailed scoring criteria for each HQ term also followed those outlined in Kwon, Lee, and Jeong (2007). HQ scores were calculated for each questionnaire item. Additionally, for each participant, a mean HQ score was computed across questionnaire items. Then, for each hypothesis, HQ scores were analyzed according to the method proposed in Kwon, Lee, and Jeong (2007). HQ scores represented an average score for the eight generated scientific hypotheses on biological phenomena. A comparison of HQ scores before and after training program instruction was made to assess changes associated with hypothesis generation training.

For this study, inter-coder reliability was calculated in accordance with Kappa's formula. The measure, frequently used in numerous psychological studies, evaluates the coding scheme and coding procedure (van Someren, Barnard, & Sandberg, 1994). A Kappa score should be above 0.70 to ensure acceptable inter-coder reliability. The inter-coder reliability of this study was acceptable (Kappa = 0.84). Significant changes in accuracy and HQs were assessed separately using an analysis of variance (ANOVA) followed by a Scheffé post-hoc test. All behavioral data was analyzed using SPSS 12.0 for Windows (SPSS Inc., Chicago, IL, USA).

Development of fMRI experimental tasks

The term "hypothesis" has a variety of different meanings in science, philosophy, and the philosophy of science. Every scholar has different diverse categories of hypothesis definition (Jeong & Kwon, 2006). Therefore, this study limits the meaning of 'hypothesis' and 'hypothesis-generating' to 'hypothesis-generating by the abductive reasoning process'. Traditionally, two types of reasoning: induction and deduction are recognized in the logic of science. However, a long line of discussion has shown that another type of scientific reasoning called retroduction or abduction, in addition to induction and deduction, exists in scientific endeavors (Kwon, Jeong & Park, 2006).

Abduction is the mental process of generating a hypothesis in which an explanation that is successful in one situation is borrowed and applied as a tentative explanation in a new situation (Hanson, 1958; Lawson, 1995; Kwon, Yang & Chung, 2000; Fisher, 2001). Also, previous studies have claimed hypotheses come, not from induction or deduction, but from prior knowledge and the creative process of abduction (Kwon, Jeong & Park, 2000; Lawson, 1995). Therefore, the term 'hypothesis-generating' in this study refers to the abductive thinking process of formulating a set of propositions proposed as tentative causal explanation for an observed scientific situation. This abductive hypothesis generation process presumably involves the reasoning procedures of exploring, combining, comparing, and selecting possible alternatives (Jeong & Kwon, 2006; Kwon, Yang & Chung, 2000; Kwon, Jeong & Park, 2006). Also, abductive hypothesis generation is regarded a learning strategy or thinking style in which one, individually, explores the cause (i.e. *explican*) for a question through self-regulation.

The term 'hypothesis-understanding' in this study refers to the thinking process of receiving new causal knowledge from a set of specific samples through inference based on an expository explanation. In this process, reasoners accept new hypotheses as causal explanations in their cognitive structure by way of temporal or logical order. Nevertheless, it does not explore suitable explican proposed by an individual as is done in the hypothesis-generating process (Kwon, Lee, Shin & Jeong, 2009; Lee & Kwon, 2008).

To control and homogenize task difficulty and the content of biological hypothesis generation tasks used as fMRI stimuli, this study developed task items in accordance with the R&D process of Borg & Gall (1989). Initially, 80 task items were designed as stimuli. Then, a pilot test of the hypothesis-generating and hypothesis-understanding tasks was administered to a group of 30 participants, none of whom participated in the actual experiment. After the pilot test, task items judged appropriate for usage in the actual experiment were selected and edited according to pilot test results. Validity and reliability of the task items were established by repeating the R&D process several times. In the end, 8 items were deemed unacceptable, 16 items were selected as pre-experiment practice tasks, and the remaining 28 items were used in the main experiment. In this study, participants partake in two separate fMRI scanning sessions: one for 'hypothesis-generating' and a second for 'hypothesis-understanding'. Employing the same phenomena in both sessions could contaminate participants' thoughts. Hence, to prevent this memory effect within the study design, the study employed two parallel-form sessions with 28 task trials for each session. The parallel-form reliability was 0.92. Moreover, the study counterbalanced problems between subjects.

F-MRI experimental task conditions and procedure

The fMRI scanning paradigm consists of two types of task conditions: hypothesis-generating and hypothesis-understanding (Fig. 1). Each task condition was applied independently to each of the two scanning sessions: hypothesis-generating and hypothesis-understanding. Each participant was scanned twice during hypothesis-generating and hypothesis-understanding, before and after the 3-month training program period.

Scanning tasks utilized a blocked design. Each task starts with a blank slide for the dummy phase (12 sec.) followed by a notice slide (12 sec.). The notice slide announces the task type (e.g. ‘hypothesis-generating’) to the participant. Then, the main task slide begins. Each session consists of 28 tasks (28 HG tasks and 28 HU tasks, a total 56 of tasks), and every task stimulus relates to biological phenomena, especially those which have causal relations. Also, each task consists of six slides. For hypothesis-generating tasks, the “*cause*” or first phenomenon is presented for 2 seconds followed by the second phenomenon, “*effect*” or its result for 2 seconds. The hypothesis-generating process by abductive reasoning is influenced by experience; in other words, prior knowledge (Kwon, Jeong & Park, 2006). That is to say, participants’ prior knowledge can either assist or interfere with hypothesis-generating. Hence, the cause is presented as a “lump” to prevent gaps among differences in participant experiences during the process of exploring explican and to make the tasks approachable. Next, a question mark is presented to participants for 3 seconds. It is at this time participants should actively generate individual hypotheses on the second phenomenon; that is, they should answer the following question, “*Why does the effect appear?*” For example, for the case illustrated in figure 1, participants may generate a hypothesis like “*Because dung is repeatedly rolled by a dung beetle’s hindlegs, it becomes ball-shaped*.” A third phenomenon is then presented for 2 seconds. The slide shows the entire process (cause + effect) to participants. Next, a response slide is presented. At this time, participants should compare their hypotheses to the third phenomenon. If the hypotheses are in agreement, participants are asked to left-click the mouse button; otherwise, they are required to right-click the mouse button. At the end of a task, a white crisscross pattern is shown to participants for 12 seconds as a baseline stimulus. The participants are instructed to keep their eyes open at all times and fixate on the central cross to minimize eye movements.

The data collected during the hypothesis-generating session was analyzed as a single block frame, [cause / effect / ? / cause + effect]. During data analysis, the ‘?’ slide phase was not extracted because it was considered a critical time point. The purpose of analysis was to examine whole neural networks at work during the hypothesis-generating process by abductive reasoning and compare them with those at work during hypothesis-understanding. In other words, it was neither relevant nor beneficial to only investigate a singular moment of causal or hypothetical explican detection. The fMRI scans, therefore, included the sub-steps of abductive reasoning.

For hypothesis-understanding, tasks are presented in the reverse order in which they were presented for hypothesis-generating tasks. In other words, the order is ‘cause → process (cause + effect) → effect (result)’. For these tasks, participants are to passively understand presented biological phenomena in causal sequence. Mirroring the hypothesis-generating tasks, a response slide is presented. At this time, participants should check their state of understanding. If they have full understanding, they are asked to left-click the mouse button; otherwise, they are required to right-click the mouse button. Also, as in the hypothesis-generating tasks, at the end of each task, a white crisscross pattern slide is presented to participants for 12 seconds.

The data for the hypothesis-understanding session tasks were also analyzed as a single block, [cause / cause + effect / effect / ?]. Data analysis, here too, did not extract the ‘?’ slide phase in order to examine whole neural networks at work during the hypothesis-understanding process and to compare them with those at work during hypothesis-generating. The fMRI images, therefore, included the whole logical process of reasoners’ causal knowledge acceptance.

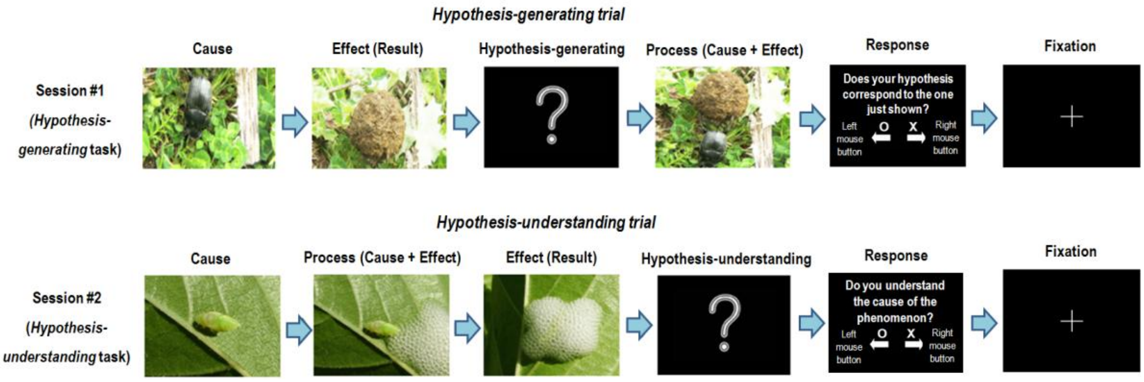

Figure 1. Schematic representation of experimental design. Each scanning session for the two investigated cases of hypothesis-generating and hypothesis-understanding consisted of 28 tasks, a total of 56 tasks. In this figure, a representative trial is presented. See the text for a thorough explanation.

F-MRI image acquisition

Anatomic T1 volume images and functional T2*-weighted magnetic resonance (MR) images were acquired with a 3.0T MR scanner (ISOL, KOREA) with standard head coil. Functional images were acquired using a T2*-weighted gradient-echo, echo planar pulse sequence (30 continuous slices parallel to the anterior-posterior commissure [AC-PC] line covering the whole brain, repetition time [TR] = 3,000 ms, echo time [TE] = 35 ms, flip angle = 80 degree, field of view [FOV] = 220 X 220 mm^2, matrix = 64 X 64, slice thickness = 5 mm). Immediately after the functional scanning, a high-resolution T1-weighted anatomic scan was acquired for each subject.

Analyses of fMRI Images and data

Image processing and statistical analysis were carried out using SPM2 (Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm) implemented on MATLAB ver. 7.0 (The MathWorks, Natick, MA). Data from one subject were discarded due to the presence of artifacts in the functional images. Moreover, the first five volumes of each subject were discarded due to T1 equilibration effects. For each subject, all volumes were spatially realigned to the first volume of the first session to correct for between-scan motion, and a mean image from the realigned volumes was created. This image was spatially normalized to the Montreal Neurological Institute (MNI) brain template (Evans et al., 1993). The derived spatial transformation was then applied to the realigned T2*-weighted volumes, which after normalization were resampled. All functional volumes were then spatially smoothed with an 8-mm full-width half-maximum (FWHM) isotropic Gaussian kernel to compensate for residual between-subject variability after spatial normalization (to allow for comparisons across subjects) and to permit application of Gaussian random field theory for corrected statistical inference (Worsley & Friston, 1995). The resulting time series across each voxel was then high-pass filtered with an upper cut-off of 128 seconds using cosine functions to remove section-specific low-frequency drifts in blood oxygen level-dependent (BOLD) signals.

Statistical maps of basic activation patterns for both the hypothesis-generating and hypothesis-understanding tasks, minus the baselines, were first computed. Data were analyzed using a random-effect model to generalize results over the population from which subjects were extracted (Friston, Holmes, & Worsley, 1999). The random-effect model was implemented using a two stage process. At the first level, for each subject, condition effects at each voxel were estimated according to the general linear model (GLM) as implemented in SPM 2 (Friston et al., 1995) and regionally specific condition effects were evaluated using linear contrasts to produce a contrast image. At the second level, the resulting contrast images from all subjects were entered into a single sample t test to assess the population mean effect. The entire process produced a statistical parametric map of the t statistics for each comparison of interest (hypothesis-generating – baseline and hypothesis-understanding – baseline) for each voxel. Maxima were reported in MNI stereotaxic coordinates for foci exceeding the highest threshold of $P < 0.001$, corrected for multiple comparisons. To avoid a false positive, only clusters bigger than 20 voxels were considered (Forman et al., 1995).

To investigate the cerebral activations preferentially evoked by the two learning strategy conditions (hypothesis-generating and hypothesis-understanding), direct statistical comparisons between the two tasks were computed at the second level (random effect). In order to accomplish this, a paired t-test analysis on individual subjects' contrast images obtained from the first level was used ($P > 0.001$ corrected). The location of foci in terms of Brodmann areas was determined using the nomenclature given by Talairach and Tournoux (1988) after correction for differences between the MNI and Talairach coordinate systems by means of a nonlinear transformation (see http://www.mrc-cbu.cam.ac.uk/~matthew/abstracts/MNITal/mni2tal. html).

Region-of-interest (ROI) analysis and hypothetical connectivity construction

All participants showed task-related brain activities, identified by contrasting the task types (hypothesis-generating and hypothesis-understanding) with the fixation as a control condition, in the frontal, parietal, temporal and occipital cortical regions and several sub-lobar regions. In this study, ROIs (regions of interest) were selected from commonly activated regions among generating and understanding groups during the same thinking conditions (Lee, 2009; Lee & Kwon, 2011). The regions were confirmed by the counter cognitive substrate method [(hypothesis-generating - baseline) - (hypothesis-understanding - baseline)] (Lee, 2009; Lee & Kwon, 2011). These activated regions were analyzed as to how connectivity changed across the conditions of hypothesis-generating and hypothesis-understanding using ROIs, which were adopted from a previous study (Lee, 2009; Lee & Kwon, 2011). ROIs were selected after analyzing significantly activated task-related brain regions when hypothesis-generating and hypothesis-understanding (Table 1) were compared. In a recent study, Lee (2009) reported that hypothesis-generating and hypothesis-understanding showed dissociative patterns at the brain network level. Lee also found two specialized core networks during hypothesis-generating and hypothesis-understanding. According to Lee & Kwon's study, the brain activation network of hypothesis-generating consisted of seven nodes, and the brain activation network of hypothesis-understanding consisted of eight nodes. Therefore, this study pre-selected these 15 ROIs (seven HG ROIs and eight HU ROIs).

The 7 ROIs adopted in this study were the left middle frontal gyrus (Fugelsang and Dunbar 2005; Kuperberg et al. 2006; Kwon et al. 2009; Lee 2009; Lee & Kwon, 2011; Parris et al. 2009; Satpute et al. 2005), the left putamen (Flaherty 2005; Lee et al. 2006; Lee 2009; Lee & Kwon, 2011), the left parahippocampal gyrus (Baird and Fugelsang 2004; Fugelsang and Dunbar 2005; Lee 2009; Lee & Kwon, 2011), the left superior temporal gyrus (Flaherty 2005; Kwon et al. 2007; Lee 2009; Lee & Kwon, 2011; Mason and Just 2004; Virtue et al. 2006; Qiu et al. 2008), the left middle temporal gyrus (Kuperberg et al. 2006; Lee 2009; Lee & Kwon, 2011; Virtue et al. 2006), the left middle occipital gyrus (Fugelsang and Dunbar 2005; Kuperberg et al. 2006;

Lee 2009; Lee & Kwon, 2011; Kwon et al. 2007), and the right lingual gyrus (Fugelsang and Dunbar 2005; Lee et al. 2006; Lee 2009; Lee & Kwon, 2011) for hypothesis-generating. In addition, for hypothesis-understanding, this study adopted 8 ROIs: the left superior parietal lobule (Fugelsang et al. 2005; Lee, 2009; Lee & Kwon, 2011), the left corpus callosum (Lee 2009; Lee & Kwon, 2011), the right corpus callosum (Lee 2009; Lee & Kwon, 2011), the left precuneus (Fugelsang et al. 2005; Lee 2009; Lee & Kwon, 2011), the right precuneus (Lee 2009; Lee & Kwon, 2011), the left lingual gyrus (Fugelsang et al. 2005; Lee 2009; Lee & Kwon, 2011), the right lingual gyrus (Fugelsang et al. 2005; Lee 2009), and the right middle frontal gyrus (Fugelsang et al. 2005; Lee 2009; Lee & Kwon, 2011). All 15 ROIs were used as a network node (i.e. seed regions) to analyze correlations among the functional connectivity structure.

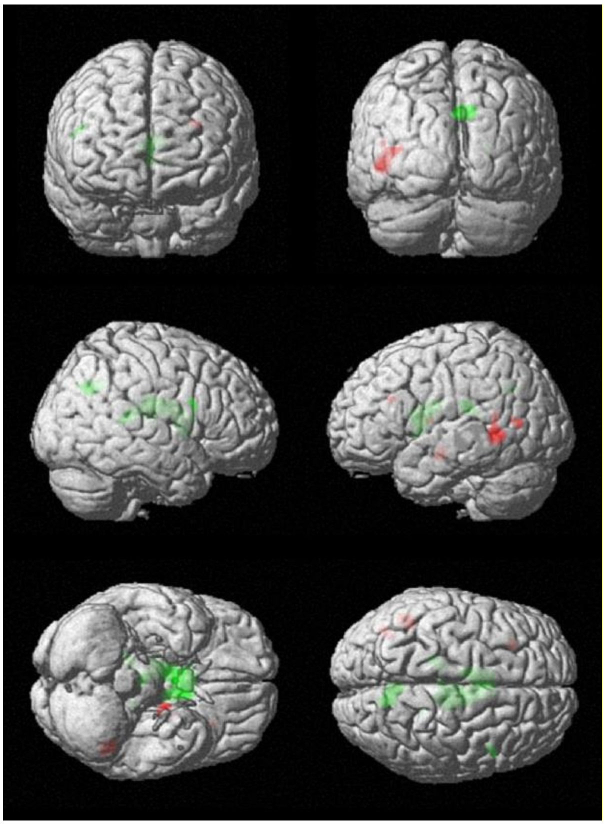

Figure 2. Graphical renderings of the regions of interest (ROIs) (Adopted from Lee & Kwon, 2011). ROIs were selected after a direct comparison of [hypothesis-generating versus hypothesis-understanding (red)] and [hypothesis-understanding versus hypothesis-generating (green)] in all participants (see Table 1 for details).

Functional connectivity analysis

To compute the measure of functional connectivity, BOLD signals of activated voxels were extracted from selected ROIs. For each participant, a mean time-course was computed across activated voxels for each ROI. A correlation coefficient was then calculated between the time-courses of pairs of ROIs (Friston, Frith, Liddle, & Frackowiak, 1993; Koshino et al., 2005; Lee, Harrison, & Mechelli, 2003).

Table 1. Regions of interest and their Talairach coordinates

Lobe	Region of activation	BA & Side	Talairach coordinates		
			x	y	z
Hypothesis-generating					
Frontal	Middle frontal gyrus	9 L	-30	26	26
Temporal	Superior temporal gyrus	39 L	-46	-49	15
	Middle temporal gyrus	22 L	-48	-49	1
Limbic	Parahippocampal gyrus	28 L	-18	-12	-9
Occipital	Middle occipital gyrus	19 L	-38	-66	11
	Lingual gyrus	18 R	8	-80	-3
Sub-lobar	Putamen	L	-24	-1	9
Hypothesis-understanding					
Frontal	Middle frontal gyrus	9 R	46	14	25
Parietal	Superior parietal lobule	7 L	-28	-62	45
	Pecuneus	7 L	-26	-68	40
		7 R	30	-70	42
Occipital	Lingual gyrus	18 L	-4	-80	-6
		18 R	8	-80	-3
Sub-lobar	Corpus callosum	R	10	-13	21
		L	-16	-28	22

To investigate total functional interconnections of participants' brain networks more effectively, this study utilized the connectivity coefficient (CC) concept suggested by Schmithorst and Holland (2006). A connectivity coefficient (CC) (CC: the weighted sum of pairwise covariances between regions, which can be expressed as the weighted sum of signed coefficients of determination between time courses from each pair of regions) can be calculated as:

$$CC_j = \sum_i W_i R_{ij}^2 \frac{R_{ij}}{|R_{ij}|}, W_i \geq 0$$

[CC_j : connectivity coefficient of the j^{th} participant, W_i (Weighted): the i^{th} weighting of each pairwise connection, *R*: correlation coefficient)]

Since a CC level provides more information than a single pairwise correlation coefficient, it is often used in analyses of functional connectivity because functionally connected networks may involve more than two interconnected regions (Schmithorst & Holland, 2006). In this study, a 3-group comparison (Fig. 3): general high school students, science high school students, and biologists, was conducted on the hypothetical network models stipulated in Lee (2009).

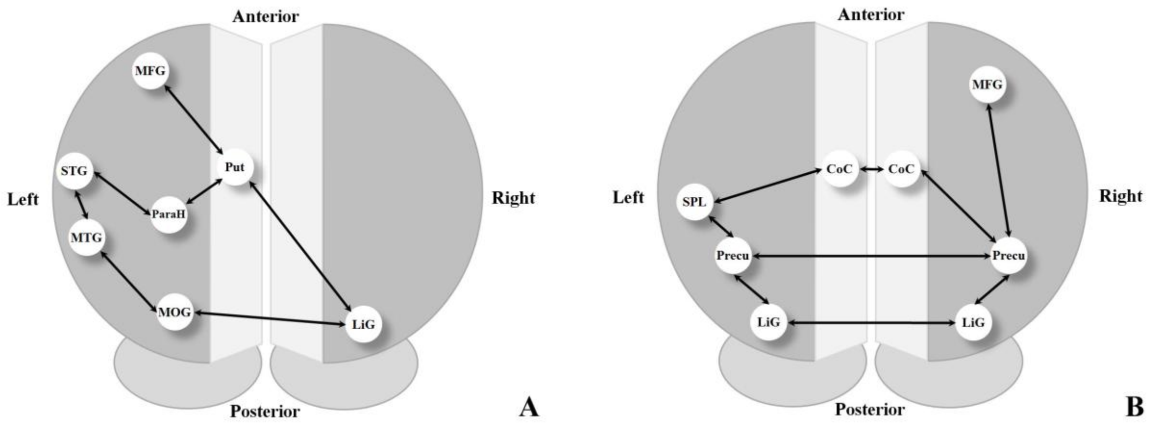

Figure 3. Hypothetical network models for (A) hypothesis-generating and (B) hypothesis-understanding (Adopted from Lee & Kwon, 2011).

Results

Behavioral Results

Two types of behavioral results were obtained from participants in this study. The first type of data pertained to trial accuracy (percentage of correct responses), and the second type of data was participants' HQ scores calculated from post-scan questionnaires.

(a) Accuracy

Since significant accuracy difference was found in the hypothesis-generating process among the three groups (Table 2), researchers conducted Scheffé's post hoc analysis. This analysis also revealed statistically significant difference among three groups during hypothesis-generating. Although there was no significant difference in accuracy for the hypothesis-understanding process among the three groups, Scheffé's post hoc analysis revealed statistically significant difference in hypothesis-understanding among the three groups (Table 2).

Table 2. Hypothesis-generating and hypothesis-understanding accuracy (%)

Learning style Group	Hypothesis-generating	*F*	*P*	Hypothesis-understanding	*F*	*P*
General-HS	95.31 ± 0.71a			98.66 ± 0.45		
Science-HS	98.81 ± 0.51b	4.692	0.015	100.00 ± 0.00	2.2	0.127
Biologists	99.70 ± 0.29 ab			100.00 ± 0.00		

Note: Mean± S.D. (Standard deviation); *different* letters (a, b) denote *significant difference* by *post hoc* of *Scheffe* ($p < 0.05$)

(b) Hypothesis explanation quotient

Significant HQ score difference was found among the three groups. Scheffé's post hoc analysis also revealed statistically significant HQ score difference among the three groups (Table 3).

Table 3. Hypothesis-generating and hypothesis-understanding HQ scores

Group	HQ scores	*F*	*P*
General-HS	3.86 ± 1.58a	363.58	0.00
Science-HS	11.61 ± 3.42b		
Biologists	31.41 ± 10.55c		

Note: Mean± S.D. (Standard deviation); *different* letters (a, b, c) denote *significant difference* by *post hoc* of *Scheffe* ($p < 0.05$)

FMRI results

(a) The hypothesis-generating functional connectivity model

A functional connectivity level comparison among the 3 groups was conducted on pre-selected ROIs. ANOVA results for the functional connectivity pairs of ROIs are shown in Fig. 4. The functional connectivity data revealed two major findings. First, there was significant difference in hypothesis-generating connectivity among the three groups. Nearly every correlation coefficient (R) for each ROI pairing was significantly different among the three groups. The four pairs of significance were: MFG (L) – Put (L) [$F(3, 35) = 27.898$, $P < 0.001$], ParaH (L) – STG (L) [$F(3, 35) = 13.969$, $P < 0.001$], STG (L) – MTG (L) [$F(3, 35) = 19.089$, $P < 0.001$], and LiG (R) – Put (L) [$F(3, 35) = 7.409$, $P = 0.002$]. When researchers conducted Scheffe's post hoc analysis, statistically significant difference was also found among these pairings for the three groups during hypothesis-generating.

Second, findings not only found significant difference in correlation coefficients (R), the weightings (W) of ROI pairs were also found to be significantly different among the three groups during the hypothesis-generating process. The six pairs showing significant difference were: MFG (L) – Put (L) [$F(3, 35) = 42.865$, $P < 0.001$], Put (L) – ParaH (L) [$F(3, 35) = 14.437$, $P < 0.001$], ParaH (L) – STG (L) [$F(3, 35) = 10.725$, $P < 0.001$], STG (L) – MTG (L) [$F(3, 35) = 34.897$, $P < 0.001$], MTG (L) – MOG (L) [$F(3, 35) = 7.879$, $P = 0.002$], and LiG (R) – Put (L) [$F(3, 35) = 8.515$, $P = 0.001$]. Scheffé's post hoc analysis confirmed statistical difference existed among the three groups during hypothesis-generating.

Figure 4 illustrates these significant differences and eases the understanding of discrepancies during the hypothesis-generating process for the 3 different groups.

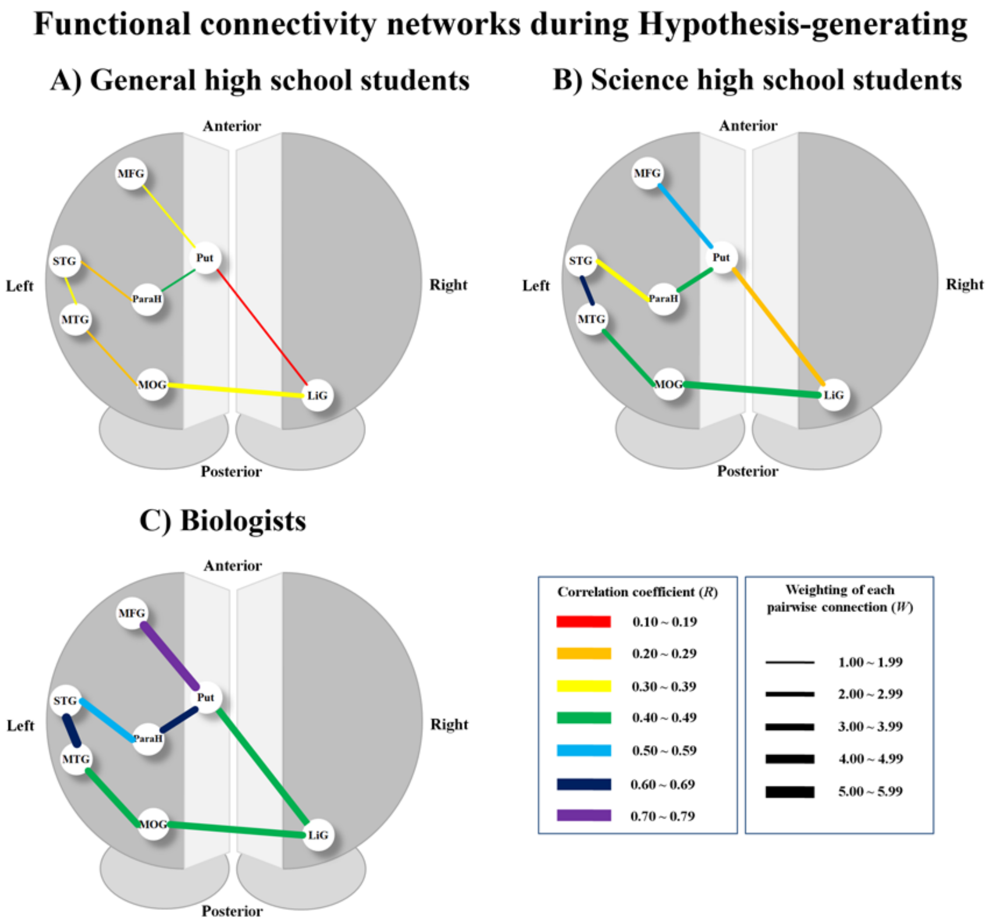

Figure 4. Significant functional connectivity networks for selected ROIs for the three groups during hypothesis-generating. The acronyms in circles represent the anatomical names of ROIs. Functional connectivity networks are: A) general high school students, B) science high school students, and C) biologists.

(b) The hypothesis-understanding functional connectivity model

A functional connectivity level 3-group comparison was conducted on pre-selected ROIs. ANOVA results for the functional connectivity pairs of ROIs are shown in Fig. 5. Functional connectivity data revealed 2 major findings. First, there was generally no significant difference in connectivity for the hypothesis-understanding process among the three groups. Although the correlation coefficients (*R*) of three ROI pairs were significantly different among three groups, all other pairings showed no significant difference. One of the three pairings that showed significant difference was the CoC (L) – CoC (R) [*F* (3, 35) = 7.991, *P* = 0.001] pairing. Scheffé's post hoc analysis also indicated that this pairing had statistical difference among the three groups for hypothesis-understanding.

There was no significant difference found among the weightings (*W*) of ROI pairs during the hypothesis-understanding process among the three groups. Likewise, there was no statistically significance difference among the three groups according to Scheffé's post hoc analysis conducted on these pairs. Figure 5 helps ease the understanding of discrepancies during the hypothesis-understanding process among the 3 different groups.

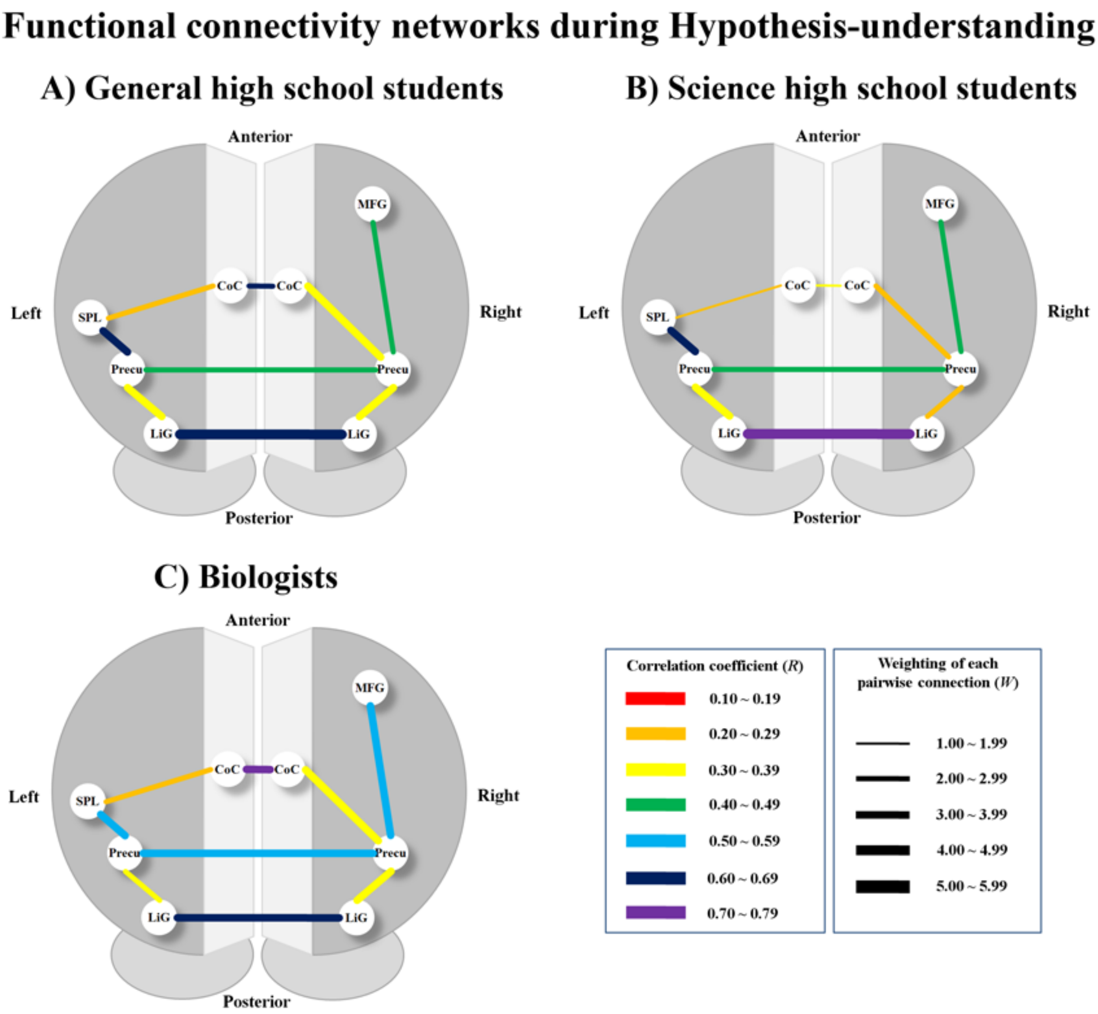

Figure 5. Significant functional connectivity networks for selected ROIs for the three groups during hypothesis-generating. The acronyms in circles represent the anatomical names of ROIs. Functional connectivity networks are: A) general high school students, B) science high school students, and C) biologists.

(c) Connectivity coefficient differences

A connectivity coefficient (CC) comparison was conducted on network models for the three groups. Two major findings were found. First, there was significant CC value difference for the hypothesis-generating process among the three groups (Fig. 6A). Scheffé's post hoc analysis also revealed statistically significant difference among the three groups for the hypothesis-generating process. The biologist group had the highest CC values among groups, and the science high school student group showed significantly higher CC values than the general high school student group. However, the CC values of the science high school student group were significantly lower than those of the biologists' (Fig. 6A).

There was no significant difference in the CC values for the hypothesis-understanding process among the three groups (Fig. 6B). Likewise, there was no significance difference found among the three groups from Scheffé post hoc analysis (Fig. 6B).

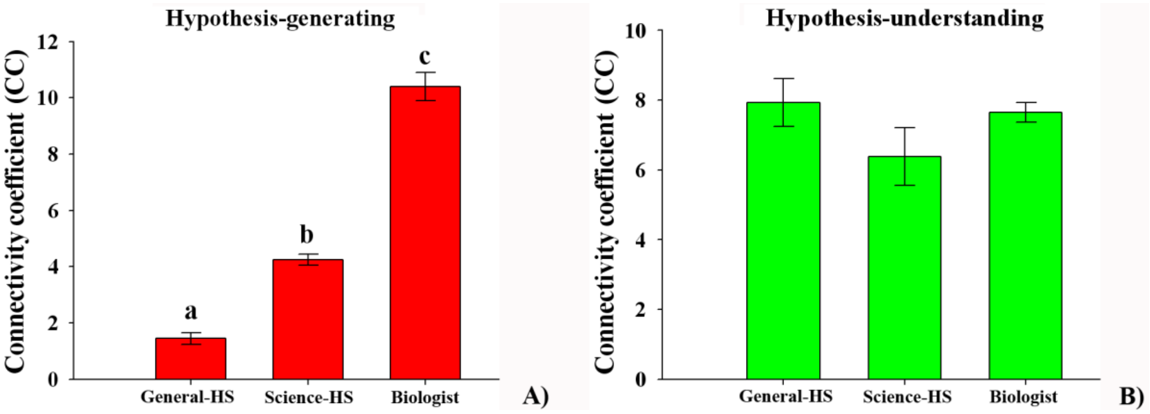

Figure 6. Plots of connectivity coefficients (CC) during hypothesis-generating (A) and hypothesis-understanding (B) from the functional connectivity networks of the three groups. Error bars represent the standard error of mean, and the *different* letters (a, b, c) denote *significant difference* by *post hoc* of *Scheffe* ($p < 0.05$)

(d) Correlations between functional connectivity and hypothesis explanation quotient

This study also conducted an investigation of correlations between CC values from the network models of the three groups (Fig. 7) and behavioral results (HQ scores) (Table 3). The investigation was carried out solely on the hypothesis-generating process because only this process showed reliable changes in functional connectivity and HQ scores among the three groups that participated in this study. That is to say, hypothesis-understanding findings did not show reliable changes. Therefore, research questions regarding correlations are specific to the effect on the hypothesis-generating process and the relationship between training-induced changes and hypothesis explanation quotients (HQ).

This study found significant correlation between HQ scores and changes in CC values ($R^2 = 0.67$, $P = 0.014$) during the hypothesis-generating process. A scatter plot of CC values, summarized in Fig. 6 as a function of individual HQ scores for the general high school students, science high school students, and biologists, is displayed in Fig. 7. In addition, this study found significant correlation for the general high school student group ($r = 0.61$, $P = 0.037$), science high school student group ($r = 0.58$, $P = 0.049$), and the biologist group ($r = 0.62$, $P = 0.033$).

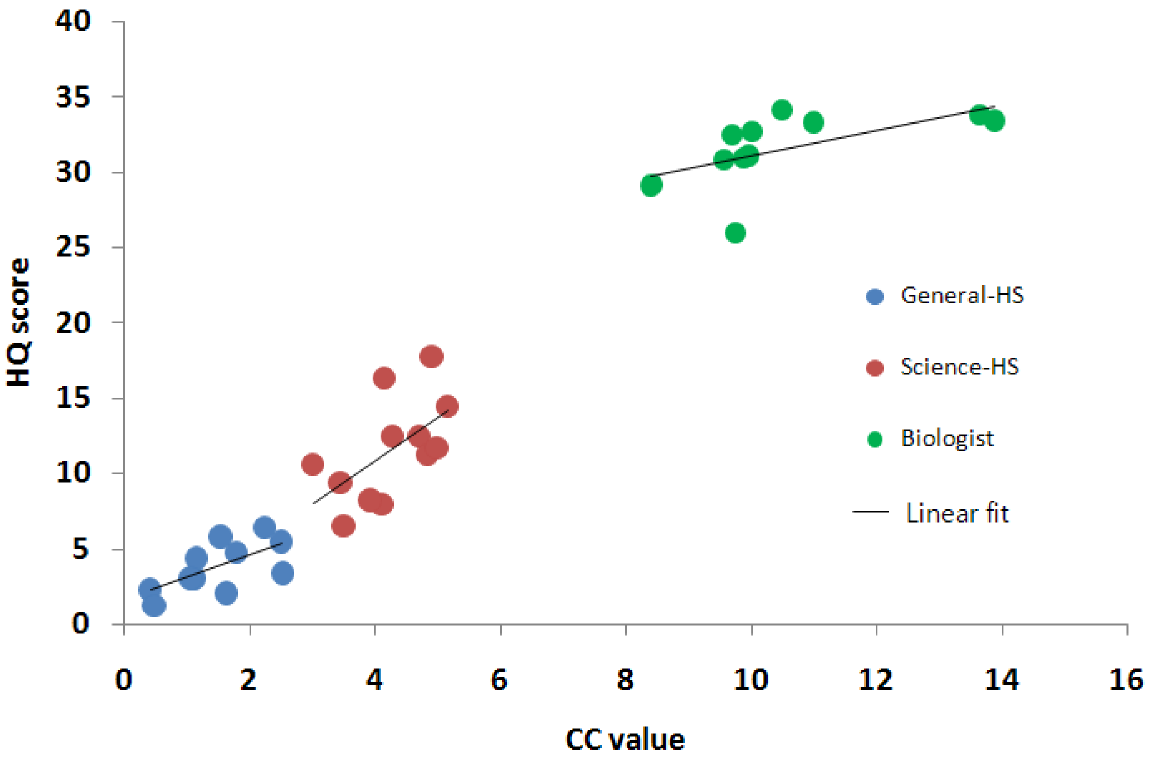

Figure 7. Scatter-plots and trend-lines of correlations between HQ scores from the three participating groups in this study along with their respective CC values. The blue circles represent general high school students, the red circles represent science high school students, and the green circles represent the biologists.

Discussion

This study explored the brain activity of healthy participants using fMRI in order to find differences in the brain networks of biologists and general and science high school students during the generating and understanding of hypotheses. The study also looked at whether differences are related to differences in functional connectivity in neural networks.

Neural connectivity differences between biologists and high school students

According to results, there are several differences in activation patterns between biologists and the high school study participants. Activation of the mesencephalon is unique to the hypothesis generation process of science high school students and biologists. Prior research has shown the mesencephalon to be a pivotal center of the mesolimbic reward system and the doparminergic pathway (Spanagel & Weiss, 1999). There is also significant difference in the MFG-Put connectivity pair. The biologist group has the highest interconnection record for this connectivity pair among the three groups (Fig. 4). This connectivity pair, also called the fronto-striatal pathway, is known as the connection means between the frontal cortex and the mesolimbic system (Cohen, Schoene-Bake, Elger, & Weber, 2009). In the past, this network connection was thought to only respond to an external reward (Spanagel & Weiss, 1999), but Mizuno et al. (2008) recently reported that the system is also closely related to the internal reward system and the academic learning motivation of an individual.

Just as prior research has shown, the biologists in this study generated knowledge and examined it through a repetitive process of inquiry (Dunbar, 2000; Kwon & Lee, 2007; Thargard, 1998). Noteworthy, the science high school students partook in more scientific experimentation than any other group (Kwon, Lee, & Jeong, 2007). Since mesencephalon activation and high putamen activation are only observed in these two groups, it can be said these two groups have a well-operating internal reward system. According to several recent studies, the academic reward system, an internal reward system, activates the putamen, which is representative of the external reward system. Activation intensities indicate both reward systems are very similar (Mizuno et al., 2005). Because the academic reward system helps form a connection between positive correlations of academic achievement motivation, activation in this region can be viewed as the core neural substrate for motivation. Evidence from this study illustrates biologists' relatively higher academic achievement motivation for biological experiments than the other two groups.

Cohen, Schoene-Bake, Elger, and Weber (2009) suggest that personality characteristics are linked to dissociable connectivity streams in the human brain. They reported that the strength of connectivity between the fronto-striatal network (tracts between prefrontal cortex and the striatum) of a novelty seeker is greater than a comfort seeker (i.e. reward dependence)'s connectivity strength. In our study, the science high school students and biologists' MFG-Put connectivity strengths are stronger than general high school students' (Fig. 4). This is consistent with Cohen et al.'s study, which claims a novelty seeker pursues a 'reward' from new experiences (e.g. buying the latest software-laden cell phone – '*smart phone*') (Cohen, Schoene-Bake, Elger, & Weber, 2009). Emerging evidence suggests that both biologists and science high school students possess this novelty seeking characteristic as it pertains to scientific inquiry. They seem to sense a 'reward' from strange new phenomenon, an experiment, a challenging problem situation, a new result, or theory construction.

Regional connectivity is responsible for differences in functional connectivity during the hypothesis-generating process, differences that appear in every pairing in the hypothetical model network except the MOG-LiG pairing. Moreover, all pairings show differences in correlation coefficients and weightings. Figure 4 shows the whole network for each group. In terms of functional connectivity, the biologist group has the highest pairwise connection correlation coefficient and weighting among the three groups while the general high school student group shows the lowest.

Because Kwon, Lee, Shin, and Jeong (2009) analyzed only simple regional functions and cognitive skills, they focused on the use of signal intensity for two particular regions. As mentioned earlier, it is not enough to simply explain complex cognitive functions such as hypothesis-generating and problem-solving. For example, Koshino et al. (2005) reported that autism subjects differed from normal subjects but only in terms of an investigation of interregional functional connectivity; they did not examine other regional activities. In that study, the autism group showed lower functional connectivity, which implies their mutual fluidity does not guarantee formation of a smooth application or transformation regardless of the type of knowledge or information they produce. In a study by Jin, Kwon, Jeong, Kwon, and Shin (2006a; 2006b) that compared a group of normal children to a group of gifted children findings revealed the two groups' brain networks work differently when generating biological hypotheses. After investigating data from EEG readings through mutual information analysis, Jin et al. found that difference lies within information transmissions. To summarize, there is a difference in how the human brain processes information. A hypothesis requires an individual to have very complex and high intelligence. Hence, it is inappropriate to explain the entire hypothesis-generating process after examination of one particular region or even a couple of pairwise connections (Jin, Kwon, Jeong, Kwon, & Shin, 2006a). This study attempted to prove the existence of differences among groups using CC values, which indicate whole network fluidity as well as relativity of time. Results provide evidence that difference in CC values do indeed exist; science high school students and biologists differ significantly from general high school students. Also, biologists score highest among the three groups (Fig. 6A). This study also shows that when it comes to generating a hypothesis through the organizing of various kinds of information, mutual connection among necessary regions is higher in biologists than the other two groups. According to regression analysis, differences in observable hypothesis-generating skills can be explained by various differences in the level of the network such as the CC value ($R^2 = 0.67$, $P = 0.014$; Fig. 7).

Emerging evidence suggests that the high CC values of the biologist group are representative of excellent information fluidity in biologists' brain networks. Also, science high school students show higher information processing skills than the other groups. For them, brain reasoning on new knowledge (e.g. a biological hypothesis) does not appear instantly, but gradually through a re-organization of prior knowledge by an abductive inference procedure (Hanson, 1958; Kwon, Jeong, & Park, 2006). Therefore, understanding sub-knowledge and information is very important for the brain to produce new knowledge. To sum up, for higher-cognitive skills such as hypothesis-generating, the limiting factor is not activation of each brain region but instead interregional correlationships (i.e. network fluidity).

While there are clear group differences in functional connectivity for the hypothesis-generating process, there are no significant group differences in either connectivity or weighting for the hypothesis-understanding process, except in three connected pairs (Fig. 5). Since it would be difficult to understand the entire process by solely examining particular regions or even a couple of connected pairs, this study focuses on group differences using CC values (Schmithorst & Holland, 2006), which indicate whole network fluidity and temporal connectivity. In terms of CC values for the hypothesis-understanding process, there was no significant difference among groups (Fig. 6B). Therefore, it has been shown that passive hypothesis-understanding was used the same pattern of neural network in all three groups, as like the case of hypothesis-generating which was used the same pattern of neural network in all three groups. In other words, the reason students in both student groups are unable to conduct an experiment as well as the biologists are not because biologists have greater hypothesis-understanding skills than students, but because biologists have greater hypothesis-generating skills than high school students.

Results of this study suggest several major differences exist in the brain functions of scientists and high school students during the processes of hypothesis-generating and hypothesis-understanding. First, biologists have a stronger connected fronto-striatal pathway, which connects to the midbrain reward system and prefrontal cortex. Second, biologists have higher CC values than high school students during the hypothesis-generating process. Third, functional connectivity network differences during hypothesis-understanding between scientists and the two high school student groups are not statistically significant. These three findings, taken together, suggest differences between biologists and high schoolers stem from motivation, or the internal reward system, and a creative mindset aimed at generating new knowledge during scientific inquiry on natural phenomena. In particular, effective synchronizing of multiple brain regions as a functional neural network when generating new, creative knowledge appears to be the key to the superior inquiry skills of biologists. In other words, as shown in a study by Kwon & Lee (2007), biologists have neither memorized vast amounts of knowledge nor do they possess the ability to quickly understand principles suggested by others. This finding has enormous ramifications for the science education field.

Correlation differences between CC values and HQ scores

This study investigated the relation between ‘CC’ values, the connectivity efficiency of a neural network, and HQ scores calculated from paper and pencil tests. According to results, there is significant relation between CC values and HQ scores for both scientists and high schoolers. Figure 6 shows biologists, science high school students, and general high school students clustered according to their respective groups on a scatter diagram. The scatter diagram indicates that functional synchronization of a neural network can discriminate groups as well as individuals’ skillfulness at scientific inquiry such as hypothesis-generating through traditional methods (e.g., paper and pencil tests).

Although general and science high school students have separate clusters, taken as a whole, the difference between scientists and high schoolers cannot be ignored. In this study, scientists and high school students are separated at a CC value of 8 and a HQ score of 25; these values form the cutting line between the two groups (Fig. 7). Findings, therefore, indicate that the measure of connectivity efficiency (synchronization) of a neural network could be an effectual alternative approach to determining similarity between students’ brains and biologists’. Particularly, this study, consistent with previous studies, measures cognitive skills through brain imaging (Chen et al., 2007; Choi et al., 2008; Eckert et al., 2008; Geake & Hansen, 2005; Reis et al., 2007; Song et al., 2008).

Educational implications

Research focused on functional connectivity network differences among groups: general high school students, science high school students, and biologists, during hypothesis-generating and hypothesis-understanding. If it were possible to somehow alter students’ brain network patterns so that they followed the patterns of biologists’, significant change would be felt in the science education field. Most previous studies on brain plasticity concentrated on finding alternative brain functions after damage to or increased activation in the brain; in particular, regions affected by training. However, this study proves that an increase in the cognitive function of high human intelligence regions cannot be produced by merely aiding activation of a particular region.

Full comprehension of the functionally synchronized brain activation network of a biologist has numerous implications for science education. First, teachers and researchers could verify the development of students’ scientific inquiry skill throughout a science class at the brain level, which would enable teachers to diagnose problematic areas quickly. Especially, full comprehension would provide educators the opportunity to objectively and quantitatively evaluate science high schoolers, who are studying science in the hope of becoming future scientists, in terms of their resemblance to actual scientists. Second, educators and researchers could develop brain-compatible textbooks or curricula that help students alter their brains in such a matter that they more closely resemble scientists′ brains by facilitating the investigation of neural network differences between scientists and high school students. Third, educators and researchers would be able to determine a student’s potential for scientific inquiry using the brain imaging technique and compare student brain networks to scientist brain networks during creative knowledge-generating. Most scientific inquiry skills have been evaluated via paper and pencil tests in the class. This traditional approach can overlook lower achieving students with weak or non-existent narrative writing skills. These students will not show a superior scientific inquiry skill and could be discounted by teachers. Findings on neural network differences between biologists and high school students from this study, if applied in the science education field, could improve the aforementioned students′ scientific inquiry skills. Through more detailed and practical instruction, these students would be able to utilize their scientific inquiry skills.

Limitations

Since this is the first study ever to have investigated high school students and biologists' learning strategies during the acts of generating and understanding a hypothesis, which are abductive inquiry processes, at the neural network level, it has several limitations regarding interpretation. Given that all participants were male, results cannot be generalized across the whole human recognition process. Furthermore, because only the functional connectivity network was analyzed, more concrete details about such issues as the direction neural network pathways follow still need to be addressed in later studies. Also, it is noted that several findings including brain regions and lateralization were already discussed in previous studies. However, this study focused on biologists. A generalization to all scientists would need additional research. Finally, given that this study only investigated the hypothesis-generating and hypothesis-understanding processes of the scientific reasoning process, this study does not claim to explain differences between generating and understanding learning strategies in all areas of the scientific inquiry process at the brain level.

Future research

This study is unique in that two different means of inferring causality in an individual's brain, hypothesis generation and hypothesis understanding, were found at the same time. The study leads the way for more related studies on the existence of similar brain network systems in female brains, and more details on aspects such as the direction neural network pathways follow and change in cortex thickness during hypotheses processes should be researched in future studies. Also, future studies need to determine the possibility of maximizing student brain activity and network fluidity related to scientific inquiry through constant training.

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Bilim adamlarının beyin ağı, onların hipotez üretmedeki üstünlüklerinin sebebi olabilir mi?

Bilim adamlarının bir yaratıcı düşünce üretirken kullandıkları üstün kabiliyetin kökeni nereden gelmektedir? Bilim adamları, genel akademik lise öğrencileri ve fen lisesi öğrencileri arasındaki bir biyoloji hipotezini üretirken hangi farklı beyin fonksiyonları aktive edilmektedir? Bu soruların beyin düzeyinde açıklamalarını ortaya çıkarmak amacıyla bu makalede genel ve fen lisesi öğrencileri ve biyologlar arasındaki sinirsel bağ farkı fMRI tekniğini kullanarak hipotez üretimi ve hipotezi anlama esnasında araştırılmıştır. Araştırmacılar biri hipotez üretimi diğeri de hipotez anlaması için olmak üzere iki set görev örneği tasarladılar. Otuz altı sağlıklı katılımcıya (her grupta on iki kişi olmak üzere) hipotez üretimi ve anlaması görevleri verildi. Sonuçlar, hipotez üretmede üstün yetenekleri olduğu sanılan biyologlar grubu için işlevsel bağlantılar için kuvvetli ara bağlantıları gösterdi. Bu grupta aynı zamanda ön-stritial yol için belgelenmiş ön kabuk ve mezolimbik sistem arasında anlamlı işlevsel bağlantı bulunmuştur. İlaveten, biyologlar grubu diğer işlevsel bağlantılarda hipotez üretme ile ilişkili olduğu bilinen daha yüksek ara bağlantılar kayıt etmişlerdir. Tümü dikkate alındığında gruplar arasındaki hipotez üretme becerilerindeki farkın ağ akışkanlığı ile ilişkili işlevsel bağlantının ara bağlantıları ile birlikte belli bölgelerin aktivasyonundan kaynaklandığı sonucuna ulaşılabilir. Özellikle, biyologların hipotez üretmedeki üstün becerileri işlevsel bağlantının kuvvetlenmiş ara bağlantılarından kaynaklanmaktadır.

Anahtar kavramlar: Lise öğrencisi, biyolog, işlevsel beyin bağlantısı, hipotez üretme, İşlevsel magnetik rözenans görüntüleme (fMRI)