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Enhancing equation comprehension with index finger writing: An fMRI study

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Abstract

Learning is a complicated process composed of vision, interpretation, comprehension and memory. This study for the first time compared activities in the brain for equation reading and writing by selected professionals using functional magnetic resonance imaging (fMRI). Finger writing did not change the message pathway in brain, but on the other hand intensified stimuli on the information integration and language processing centers by hand movement. Writing practice can assist students to integrate and comprehend the lectures delivered in the chemical engineering classrooms. However, this practice cannot help a student to extract abstract meaning in the equation.

Keywords: Writing; Brain; fMRI; Chemical engineering education

1. Introduction

Bain activity can be monitored by functional brain imaging and mapping techniques (Crinion *et al.*, 2006; Kobayashi *et al.*, 2006; Sugihara *et al.*, 2006). Learning consists of vision, comprehension, reasoning, and information storage. Brain imaging research into mathematic implementation is still limited (Tang *et al.*, 2006). However, building modeling capability for a physical phenomenon using differential equations is central to chemical engineering education (Arlabosse and Chitu, 2007; Hwang *et al.*, 2006; Islam *et al.*, 2007; Kung, 2006; Lee *et al.*, 2006, 2007; Otawara and Kitamura, 2006; Seginer and Bux, 2006; Seginer *et al.*, 2007; Tao *et al.*, 2006; Tien and Ramarao, 2006).

Wang *et al.* (2008) for the first time measured the brain activities in joke and equation reading. These authors noted that the equation message was received by V1 then was sent through the left superior parietal lobule (Brodmann area 7 in area 3e) and middle frontal gyrus (Brodmann area 6, BA 6) to the superior frontal gyrus (BA 8 and 9) and Broca area (BA 45). The brain was confirmed to process equations as a syllabary was primarily identified by its shape rather than identity.

The ultimate interest on brain research is to realize how brain works, and how one can in some sense manipulate brain functions. This series work aims at exploring ‘‘what works’’ in chemical engineering classrooms. It is commonly accepted that learning is efficient when material reading is accompanied with writing practice. However, current lecturing often encompasses fancy slide presentation with printed notes provided, which acquires less writing than before on students. We investigated herein how the brain was activated in reading and writing equation. In particular, this study noted a possible correlation between activated areas in brain in hand writing and in equation comprehension.

2. Materials and methods

2.1. Subjects, tasks and stimuli

Right-handed university professors aged 32–46 years, who were native Chinese speakers with no history of neurological disorders, participated in this study. Written consent was obtained from all subjects.

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Two block designs were utilized: (1) reading the following heat conduction equation silently, $\rho C_p(\partial T/\partial t) = k(\partial^2 T/\partial x^2) + \dot{q}$; (2) reading silently and writing using right index finger the equation mentioned in (1). For comparison sake, the joke cited in Wang *et al.* (2008) was used replacing equation in some tests.

The two tasks were blocked in a random order and interleaved with the fixation condition in each experimental session. For each block test, two scanning periods were utilized: (1) when one of the two tasks was performed, and, (2) a rest period (baseline). Each block continued for 600 s, and a task and rest period were repeated 10 times.

Stimulus presentation was controlled by a PC. Stimuli were projected via an LCD projector onto a screen located at the subject's feet. Each subject could clearly see the screen at a viewing distance of roughly 2 m.

2.2. MRI procedures and image analysis

Echo planar imaging (EPI) was performed using a 3 T GE Sigma LX system with a standard head coil. The $T2^*$-weighted time-series images depicting blood oxygenation level-dependent (BOLD) contrast were acquired using a gradient-echo EPI sequence (TR = 2 s; TE = 25 s; flip angle = 90°; FOV = 24 cm × 24 cm; 64 × 64 matrix; in-plane resolution, 3.75 mm × 3.75 mm). Thirty-five axial contiguous 4-mm-thick slices covering the whole brain were collected. Each block for each condition lasted for 15 volumes (the instruction for 2 s = 1 vol, and each task period was 30 s = 15 vol). Here, 150 volumes were obtained in a single session. Structural high-resolution T1 images were also collected prior to experimental sessions (TR = 10.212; TE = 4.856; flip angle = 90°; FOV = 24 cm × 24 cm; 521 × 512 matrix; 172 slices; 0.9 mm thick; no gap).

Data were analyzed using Statistical Parametric Mapping (SPM2) (Wellcome Department of Cognitive Neurology, London), running under Matlab 7.0.0 (Mathworks, Sherbon, MA, USA). The first four scans were excluded from the analysis to minimize T1 relaxation artifacts; the remaining 146 volumes were processed. No slice timing correction was applied. All volumes were realigned to the first volume with 4th-degree B-spline interpolation. The volumes were then resliced. A mean EPI image was derived, to which the individual T1 image was coregistered. Individual T1 images were spatially normalized to the Montreal Neurological Institute (MNI) T1 template (2 mm × 2 mm × 2 mm) of SPM2 with medium nonlinear regularization. Transformation parameters were derived from this process, and parameters were then applied to individual T1 images and to all EPI images. Individual T1 images were resampled into 1 mm × 1 mm × 1 mm voxels, and EPI images were resampled into 3 mm × 3 mm × 3 mm voxels with 4th-degree B-spline interpolation. Finally, the EPI images were smoothed with a Gaussian kernel of an 8-mm isotropic full wave at half-maximum.

Statistical analyses were conducted using SPM2. Functional data were evaluated as a block design using a general linear model approach. Each subject's dataset consisted of 300 volumes, which were collapsed into two conditions (*i.e.*, task and RE) images with SPM's canonical hemodynamic response function (HRF) with a time derivative. Global scaling was not employed. High-pass temporal filtering with a cut-off of 128 s was applied, and serial autocorrelations were modeled with an AR(1) model in SPM2.

3. Results and discussion

3.1. Equation reading and writing

Fig. 1(a) and Table 1 present the significant brain activation during equation reading and writing vs. fixation ($p < 0.001$, uncorrected).

During equation reading and writing, seven activation areas were identified. Activation area 1 is composed of 2688 voxels, peaking at [30, −87, −18], primarily constituting the left cerebrum (36.8%) and right cerebrum (41.7%). Detailed sub-areas were sub-gyral [left (3.0%) and right (1.9%)], fusiform gyrus [left (2.2%) and right (4.3%)], inferior occipital gyrus [left (2.1%) and right (4.9%)], lingual gyrus [left (9.8%) and right (10.9%)], middle occipital gyrus [left (7.6%) and right (10.0%)], cuneus [left (6.1%) and right (9.4%)], precuneus [left (3.4%)], superior parietal lobule [left (2.0%)], declive [left (1.4%) and right (7.9%)], culmen [right (1.5%)]. These activation areas incorporated the BA 7 [left (2.1%)], 17 [left (1.9%) and right (3.1%)], 18 [left (7.0%) and right (8.7%)], 19 [left (2.5%) and right (4.1%)].

Activation area 2 is composed of 894 voxels, peaking at [−33, 6, −60], principally constituting the left cerebrum (88.1%). Detailed sub-areas were sub-gyral [left (2.9%)], precentral gyrus [left (43.7%)], inferior frontal gyrus [left (4.14%)], inferior parietal lobule [left (5.7%)], middle frontal gyrus [left (14.0%)], postcentral gyrus [left (15.1%)], superior frontal gyrus [left (2.2%)]. This activation area encompassed BA 1 [left (0.3%)], 2 [left (0.3%)], 3 [left (7.4%)], 4 [left (8.1%)], 6 [left (21.5%)], 9 [left (1.1%)], 40 [left (2.4%)], 44 [left (0.7%)], 45 [left (0.3%)].

Activation area 3 is composed of 120 voxels, peaking at [−33, −6, 60], generally comprising the right cerebrum (77.5%). Detailed sub-areas were the precuneus [right (40%)] and superior parietal lobule [right (36.7%)]. This activation area incorporated BA 7 [right (41.5%)].

The activation area 4 is composed of 70 voxels, peaking at [−33, −6, 60], principally the inter-hemispheric (15.7%) and left cerebrum (84.3%). Detailed sub-areas were superior frontal gyrus [left (32.9%) and central (1.4%)], medial frontal gyrus [left (48.6%) and central (1.4%)]. This activation area included the Brodmann areas 6 [left (54.3%)].

The activation area 5 is composed of 58 voxels, peaking at [45, −6, 57], mainly constituting the right cerebrum (87.9%). Detailed sub-areas were precentral gyrus [right (41.4%)], middle frontal gyrus [right (46.6%)]. This activation area incorporated the BA 6 [right (50.0%)].

The activation area 6 is composed of 37 voxels, peaking at [9, −72, −45], principally constituting the right cerebrum (91.9%). Detailed sub-areas were Pyramis of Vermis [central (2.7%)], Tuber of Vermis [central (2.7%)], inferior semi-lunar lobule [right (37.8%)], uvula [right (16.2%)], pyramis [right (32.4%)]. This area incorporated with no Brodmann area.

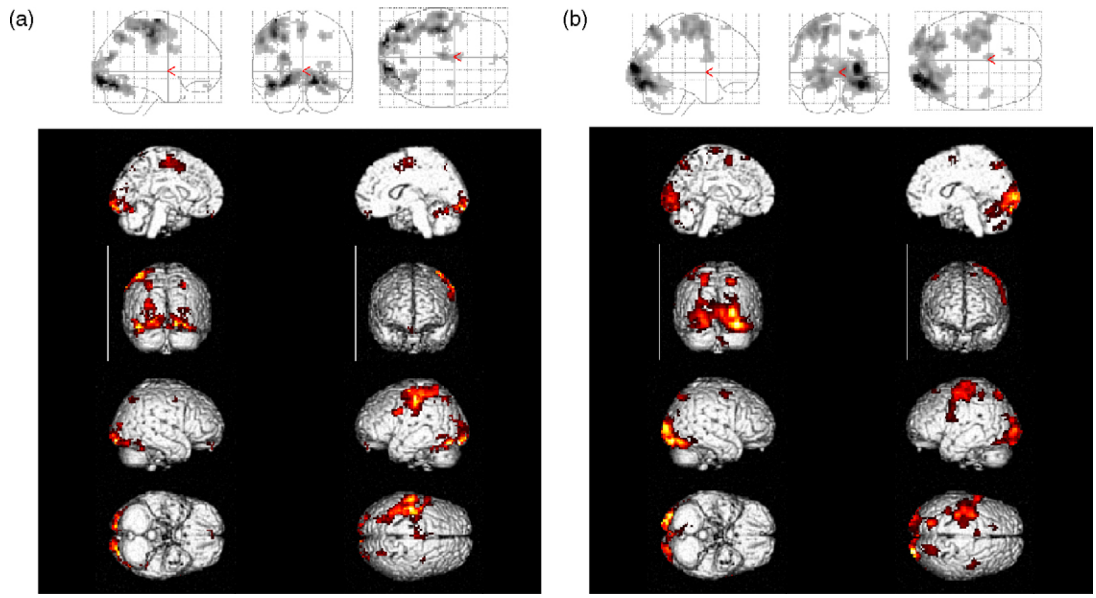

Fig. 1. Group-averaged maps for equation reading and writing (a) and joke reading and writing (b) relative to the fixation yielded from the scans onto a standard MNI template by SPM2. Clusters with an uncorrected $p < 0.001$ with spatial extent >20 were shown.

Table 1
Activation during equation reading and writing

Activated region (approximate BA)	Left/Right	MNI coordinates			Number of voxels
		x	y	z	
Fusiform gyrus (BA 18)	R	30	−87	−18	2688
Middle frontal gyrus	L	−33	−6	60	894
Precuneus	R	21	−69	51	120
Medial frontal gyrus (BA 6)	L	−3	3	57	70
Precentral gyrus (BA 6)	R	45	−6	57	58
Cerebellum	R	9	−72	−45	37
Superior frontal gyrus (BA 6)	L	−15	27	63	15

The activation area 7 is composed of 15 voxels, peaking at [−15, 27, 63], mainly constituting the left cerebrum (80%). The detailed sub-area was the superior frontal gyrus [left (80%)]. The BA incorporated with the activation area is 6 [left (53.3%)].

3.2. Joke reading and writing

For comparison, the joke reading with right index finger writing were tested and shown in Fig. 1(b) and Table 2 ($p < 0.001$, uncorrected).

During equation reading, seven activation areas were identified. Activation area 1j is composed of 1014 voxels, peaking at [36, −15, 69], primarily constituting the left cerebrum (85.8%). Detailed sub-areas were sub-gyral [left (2.5%)], precentral gyrus [left (25.3%)], inferior frontal gyrus [left (5.1%)], inferior parietal lobule [left (10.0%)], precuneus [left (3.6%)], superior parietal lobule [left (5.3%]], middle frontal gyrus [left (4.4%)], postcentral gyrus [left (29.7%)]. These activation areas incorporated the BA 1 [left (1.5%)], 2 [left (5.4%)], 3 [left (7%)], 4 [left (4.7%)], 5 [left

Table 2
Activation during joke reading and writing

Activated region (approximate BA)	Left/Right	MNI coordinates			Number of voxels
		x	y	z	
Precentral gyrus	L	−36	−15	69	1014
Declive	L	−42	−75	−18	916
Medial frontal gyrus (BA 6)	L	−3	−15	54	178
Cerebellum	R	33	−54	−27	79
Superior parietal lobule	R	27	−66	45	41
Middle frontal gyrus	R	36	−6	45	19
Declive	R	42	−57	−21	17
Orbital gyrus (BA 11)	R	9	51	−21	15

(0.4%)], 6 [left (9.2%)], 7 [left (4.1%)], 9 [left (3.2%)], 40 [left (14.8%)].

Activation area 2j is composed of 916 voxels, peaking at [−42, −75, −18], principally constituting the left cerebrum (53.3%) and right cerebrum (31.9%). Detailed sub-areas were sub-gyral [left (5.13%) and right (0.87)], fusiform gyrus [left (5.35%) and right (1.86)], inferior occipital gyrus [left (6.11%) and right (6.44)], inferior temporal gyrus [left (1.31%)], lingual gyrus [left (14.30%) and right (12.77)], middle occipital gyrus [left (12.45%) and right (4.69)], cuneus [left (6.55%) and right (4.91)], declive [left (3.28%) and right (1.97)], culmen [left (1.97%) and right (1.09)]. This activation area encompassed BA 17 [left (4.04%) and right (4.04%)], 18 [left (8.62%) and right (5.02%)], 19 [left (3.93%)], 37 [left (1.09)].

Activation area 3j is composed of 178 voxels, peaking at [−3, −15, 54], generally comprising the inter-hemispheric (15.2%), left cerebrum (65.2%) and right cerebrum (19.7%). Detailed sub-areas were the cingulate gyrus [left (6.2%), right (0.6), and central (1.1)], middle frontal gyrus [left (1.7%)], paracentral lobule [left (1.1%)], superior frontal gyrus [left (5.6%) and central (1.1%)], medial frontal gyrus [left (40.5%), right (19.1%), and central (7.9)]. This activation area incorporated BA 6 [left (29.2%) and right (17.4%)], 24 [left (2.3%)], 32 [left (4.5%)].

The activation area 4j is composed of 178 voxels, peaking at [−3, −15, 54], mainly constituting the right cerebrum (100%). Detailed sub-areas were sub-gyral [right (4.9%)], inferior parietal lobule [right (2.4%)] precuneus [right (19.5%)], superior parietal lobule [right (73.2%)]. This activation area incorporated the BA 7 [right (43.9%)].

The activation area 5j is composed of 41 voxels, peaking at [33, −54, −27], principally the right cerebrum (100%). Detailed sub-areas were declive [right (51.9%)], culmen [right (48.10)]. No Brodmann areas were associated with this activation area.

The activation area 6j is composed of 19 voxels, peaking at [36, −6, 45], principally constituting the right cerebrum (91.9%). Detailed sub-areas were sub-gyral [right (5.3%)], precentral gyrus [right (10.5%)], middle frontal gyrus [right (84.2%)]. This area incorporated BA 7 [right (42.1%)].

The activation area 7j is composed of 17 voxels, peaking at [42, −57, −21], mainly constituting the right cerebrum (100%). The detailed sub-areas were sub-gyral [right (5.9%)], fusiform gyrus [right (94.1%)]. The BA 37 was incorporated with this activation area [right (41.8%)].

3.3. Brain processing

As Wang *et al.* (2008) addressed, the joke reading signal was sent from visual processing areas [V1–3] (BA 17–19) to the left superior parietal lobule (BA 7, Somatosensory Association Cortex) via a dorsal stream for conscious awareness. Further processing was generally weak. On the other hand, the equation reading was sent from [V1–3] through the left superior parietal lobule (BA 7) and middle frontal gyrus (Brodmann area 6) to the superior frontal gyrus (BA 8 and 9) and Broca area (BA 45). Some of the message was also sent to Wernicke's area (BA 40) from Broca's area via the arcuate fasciculus, and to the inferior and middle temporal gyrus (BA 20 and 21).

The present fMRI results revealed that finger writing did not change the message pathway, but had enhanced the stimulation in certain brain areas. Owing to hand movement involved, the stimulation on Brodmann areas 1–4 was obvious in all finger writing tests. On joke reading and writing, a total of 42 and 71 voxels on the left and right superior parietal lobule (BA 7), and 142 volexs were fired for the left middle frontal gyrus (BA 6), respectively, much higher than those recorded for silent joke reading only (13, 0 and 5 voxels, respectively) (Wang *et al.*, 2008). Additionally, the left superior frontal gyrus (BA 8 and 9) was fired in joke reading and writing test, which was not noted in the silent reading test. Such an occurrence indicated that finger writing did stimulate more brain areas at higher intensities than simple silent reading.

On equation reading and writing, the stimuli on BA 6, 7, 9, and 40 were all increased. For instance, 170 voxels were fired on the left middle frontal gyrus (BA 6), much higher than that noted for silent equation reading (64). Finger writing activated Brodmann areas 1–3, probably hence strongly stimulating the dorsal pathway via Brodmann areas 7 and 6. On the other hand, writing had no significant effects on left middle frontal gyrus or Broca area (BA 44 and 45). Restated, finger writing has no effect on abstract meaning comprehension. Learning with writing practice should be beneficial to student for summarizing and comprehending information delivered in chemical engineering classrooms. However, writing could not significantly assist equation interpretation.

4. Conclusions

Teaching how to use differential equations to describe physical phenomena is essential in Chemical Engineering education. This work for the first time compared the brain activity in differential equation reading and writing by selected professionals using fMRI. In silent reading test, as Wang *et al.* (2008) addressed, the equation reading signal is sent from visual processing areas through the left superior parietal lobule (BA 7) and middle frontal gyrus (BA 6) to the superior frontal gyrus (BA 8 and 9) and Broca area (BA 45). Finger writing does not change this message pathway, but firing the Primary Somatosensory Cortex (BA 1–3) and Primary Motor Cortex (BA 4) to enhance stimuli on BA 6 and 7. Wiring practice assists students to integrate and comprehend the lectures delivered in the classrooms, but cannot help extracting abstract idea therein involved.

References

Arlabosse, P. and T. Chitu, "Identification of the Limiting Mechanism in Contact Drying of Agitated Sewage Sludge," *Dry. Technol.*, **25**, 557 (2007).

Crinion, J., R. Turner, A. Grogan, T. Hanakawa, U. Noppeney, J. T. Devlin, T. Aso, S. Urayama, H. Fukuyama, K. Stockton, K. Usui, D. W. Green, and C. J. Price, "Language Control in the Bilingual Brain," *Science*, **312**, 1537 (2006).

Hwang, K. J., S. F. You, and T. M. Don, "Disruption Kinetics of Bacterial Cells during Purification of Poly-beta-hydroxyalkanoate Using Ultrasonication," *J. Chin. Inst. Chem. Engrs.*, **37**, 209 (2006).

Islam, M. R., K. S. Thaker, and A. S. Mujumdar, "A Diffusion Model for a Drum Dryer Subjected to Conduction, Convection, and Radiant Heat Input," *Dry. Technol.*, **25**, 1033 (2007).

Kobayashi, C., G. H. Glover, and E. Temple, "Cultural and Linguistic Influence on Neural Bases of 'Theory of Mind': An fMRI Study with Japanese Bilinguals," *Brain Lang.*, **98**, 210 (2006).

Kung, H. H., "Nanotechnology: Opportunity for Chemical Engineering," *J. Chin. Inst. Chem. Engrs.*, **37**, 1 (2006).

Lee, D. J., J. Y. Lai, and A. S. Mujumdar, "Moisture Distribution and Dewatering Efficiency for Wet Materials," *Dry. Technol.*, **24**, 1201 (2006).

Lee, J. E., J. K. Lee, and H. K. Choi, "Filter Press for Electrodewatering of Waterworks Sludge," *Dry. Technol.*, **25**, 1649 (2007).

Otawara, K. and T. Kitamura, "Comparison of a Belt-Filter and Centrifuge in the Crystal Purification Process with CDC (Cooling Disc Crystallizer) and KCP (Kureha Crystal Purifier)," *J. Chin. Inst. Chem. Engrs.*, **37**, 509 (2006).

Seginer, I. and M. Bux, "Modeling Solar Drying Rate of Wastewater Sludge," *Dry. Technol.*, **24**, 1353 (2006).

Seginer, I., I. Ioslovich, and M. Bux, "Optimal Control of Solar Sludge Dryer," *Dry. Technol.*, **25**, 401 (2007).

Sugihara, G., T. Kaminaga, and M. Sugishita, "Interindividual Uniformity and Variety of the "Writing Center: A Functional MRI Study"," *NeuroImage*, **32**, 1837 (2006).

Tang, Y. Y., W. T. Zhang, K. W. Chen, S. G. Feng, J. Ye, J. X. Shen, E. M. Reiman, and Y. J. Liu, "Arithmetic Processing in the Brain Shaped by Cultures," *Proc. Natl. Acad. Sci.*, **103**, 10775 (2006).

Tao, T., X. F. Peng, and D. J. Lee, "Interaction between Ice and Floc under Freezing," *J. Chin. Inst. Chem. Engrs.*, **37**, 299 (2006).

Tien, C. and B. V. Ramarao, "On Analysis of Cake Formation and Growth in Cake Filtration," *J. Chin. Inst. Chem. Engrs.*, **37**, 81 (2006).

Wang, X. D., M. T. Wang, and D. J. Lee, "Neuroimaging Study of Partial Differential Equation Reading in Brain," *J. Chin. Inst. Chem. Engrs.*, **39**, 301 (2008).