A Review: Fundamental and Applications of functional Magnetic Resonance Imaging (fMRI) on brain learning activities

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Abstract: - Brain activities also known as neuron activities, and its learning activities are defined as the brain’s ability to learn. Learning is part of the dynamic brain process. It consists of visions, comprehension, reasoning, and information storage. By searching deeply into the cellular level of a brain’s operation and by considering the function of the interconnected neurons, it enables us to learn and memorize. Nowadays, there are many brain imaging technologies that enable people to study the activity arising from a large group of neurons instead of only the behavior of single neurons. Since 1990s, the application of fMRI has rapidly increased and numerous experiments and studies relating to human brain activities have been conducted. Mental arithmetic as a higher mental development has been a focus in this neuroimaging study to identify the connection between several number of factors and significant brain region activations.

Key-Words: - Brain activations, fMRI applications, brain learning activities, mathematical thinking, neurons development, BOLD fMRI

1 Introduction

Brain is one of the most extraordinary features of a human. The human brain accommodates nearly 100 billion nerve cells and weigh about 1.35kg. It consists of 40% of gray matter and 60% of white matter within the skull. There are four different lobes inside the brain such as temporal lobe, parietal lobe, frontal lobe and occipital lobe. By interacting with the world through perception and action, the human brain learns and grows. It is also capable to adapt and rewire itself continuously. To develop the embryos, nerve cells travel to their eventual region of the brain. Once they have settled down, the neurons will continue to grow and develop within its region of the brain. As a fetus grows, these neurons compete for a limited space among each other. Moreover, those that do not find a place to live and thrive are prune back and demolished.

Meanwhile, billions of neurons that successfully travel to the designated regions of the brain will form a foundation of the brain by creating an appropriate connection and patterns. These neurons activities represent the brain activities, which are known as mental activities. The transmission of information substantially occurs with the neural networks development of neurons and fibers connection. Generally, when the brain matures, numerous fibers develop and the brain becomes increasingly interconnected. This interconnected network of neurons is important to the configuration of memories and the attachment of new learning to previous learning.

The ability of a human to learn is due to a dynamic process of neuronal functioning known as adaptive plasticity. Based on Hebb’s Model, the learning process is done through synaptic plasticity, which is a repetition of coincident firing that may result in a high efficiency of information being conveyed across the synapses through biochemical processes. Statistically, 75% of all information gain access to the brain through human visual system. Besides, simultaneous seeing and hearing the same information works more effectively compared to doing it separately. Moreover, most of fMRI studies...
were conducted using visual approach by applying typical on-off block design [1] and projected LCD [2–4]. Thus, these approaches activate the primary visual cortex, which leads the information processing into two types of neuronal pathways. This information can be processed either through dorsal pathway or ventral pathway. Dorsal pathway occurs when neural network reaches up into the parietal lobe while ventral pathway happens when the neural network reaches down into the temporal lobe. These different pathways are shown in Fig.1.

Fig.1: The difference between dorsal and ventral pathways.

The objectives of this review paper are to explain the basic principles of brain and fMRI, to summarize the previous research on applications of fMRI especially on mathematical thinking and to gain understanding on what factors can affect the ability of a person to do mathematics.

This paper is divided into 4 sections which are as follows: the first section opens with a brief introduction on brain physiology and its relationship with one method of brain learning, which is mental arithmetic, while the second section explains the fundamentals of functional Magnetic Imaging Resonance (fMRI) and its operational principles. Besides mental arithmetic, other studies using the application of fMRI are briefly provided in the third section. Finally, the fourth section summarizes the paper, and briefly explains factors that influence people’s ability in doing mathematics.

1.1 Mental Arithmetic and the brain
This section will briefly explain and summarize how mental arithmetic affects the neuronal function of the brain regions. It is known that mental arithmetic is one of the higher processes of brain activities and it is employed as a paradigm to study the higher order of mental processes [5]. Mental arithmetic requires an integration of multiple cognitive function including number identification, retrieval of arithmetic facts, temporary storage of intermediate results and manipulation of mental representations [6]. Moreover, people today tend to rely on physical devices such as pencils and papers, mechanical calculator, slide rules, abacus and more recently digital computer to solve complex calculations.

The ability to do mathematics involves learning, memorizing and thinking aptitude inside the brain. Therefore, these processes usually involve investigating into the cellular level of the brain’s function. This is reflected on the neurons operating. Note that a human brain comprises of approximately 100 billion neurons, which are pivotal interconnected information processing cells. Psychologically, mental arithmetic involves a feed forward and feedback circuit between certain parts of the brain such as bilateral parietal, prefrontal, premotor and motor cortices as well as hippocampus.

A previous study [7] shows that arithmetic activities depend on the collaboration of neural system carried by diverse functional modules established in a number of distinct parts of the brain. It states that there is no particular brain or modules for performing arithmetic. On the other hand, Dehaene etc. [7] found that the collaboration of neural system during arithmetic performing involves the left and right fusiform gyri (imaging the number), bilateral parietal cortices (number sense), lateral and medial parts of the temporal lobe (arithmetic memories) and inferior parts of the frontal lobes (working memory and decision making). Moreover, it is proved that different style of individual problem-solving strategies during mental calculation, determine different cortical activation area [4-5].

Fig. 2 : Different strategies may result in one or more different brain area activation.
Figure 2 shows that different problem-solving strategies may generate different parts of the brain area. Either visual strategy or verbal strategy activates a number of the same brain regions such as left-dorsolateral prefrontal and premotor cortex. For Visual strategy, the brain shows a significant activation on angular gyrus while for verbal strategy, there is a significant activation on Broca’s area which reflects the verbal cortex.

Abacus-based mental calculation is an extensive strategy for mathematical calculation. It is an attribute of the Chinese culture and this abacus-based mental calculation technique is quite different [1]. The most significant area of the brain that is activated during mental arithmetic among abacus experts is the left-posterior superior parietal cortex while the right frontoparietal activate indicates the neural substrates sub serving visuospatial processing [2,7]. Currently, there are various imaging techniques, which allow researchers to conduct studies and experiments that are related to the physiological changes that accompany the brain activation. These techniques are not only different in measurement, but also different in providing the temporal and spatial resolution.

For fMRI, when the neural activities increase, it will increase the blood oxygen flow and thus, the fMRI signal will increase.

2 Functional Magnetic Resonance Imaging (fMRI)

Functional Magnetic Resonance Imaging (fMRI) is a common tool for “brain mapping” in cognitive neuroscience. It is one of the non-invasive techniques used for imaging the activation of brain areas by various types of physical sensation or activity, problem solving and movement. Therefore, this section will briefly describe the fundamental principle of fMRI, which will influence the quality of fMRI image data.

With the aid of Magnetic Resonance Imaging (MRI) and an additional response signal, fMRI can image the changes of blood oxygen level in the active areas of the brain. fMRI allows the procedure to detect the differentiation of cerebral blood oxygen level generated by the brain activities of a subject in response to dissimilar sensory motor or cognitive task. Neural activities in the brain are closely linked to the changes in blood flow and blood oxygenation. Red blood cells from local capillaries consist of oxygen conveyed by the hemoglobin. When neuron cells are active, the oxygen level will deplete. The local response to this oxygen depletion refers to an increase in blood flow to an area of increased neural activity.

Blood Oxygen Level Dependent (BOLD) fMRI is a method used to observe which regions of the brain are active at any given time. BOLD fMRI techniques are used to measure primarily changes in blood oxygenation. A lot of energy is required when neurons are actively firing since these neurons do not have internal reserve of energy such as in the form of glucose and oxygen. Through hemodynamic response process, oxygen released from the blood to the active neurons is at a greater rate compared to inactive neurons. Thus, MRI scanner will detect the magnetic signal variation leads by the differences in magnetic susceptibility between oxyhaemoglobin and deoxyhaemoglobin. This magnetic signal variation is due to the behavior of the hemoglobin. Oxygenation hemoglobin is diamagnetic while the deoxygenated hemoglobin is paramagnetic. Therefore, the level of oxygenation influences the variation in magnetic resonance (MR) signal of the blood. These variation signals can be detected using an appropriate MR pulse sequence and known as
BOLD response. The concentration of deoxyhaemoglobin affects the intensity of image captured by the fMRI machines. When the concentration of deoxyhaemoglobin increase, image intensity will decrease and vice versa.

This fundamental principle of fMRI enables people to investigate and understand not only which brain regions are involved in the specific cognitive task but further research on fMRI data may allow us to know what functions are performed by each regions of the brain and how they are performed.

3 Applications of functional MRI in research studies
Numerous studies have been conducted to detect brain activation based on various cognitive tasks in order to identify specific brain role. Wang et al. reported that there are 10 significant areas activated during partial differential reading [11] including primary visual cortex, left superior parietal lobule, middle frontal gyrus and broca area. This significant area indicates the neuronal pathways of reading message activity.

Besides that, fMRI has been widely used in research studies regarding the underlying neural circuitry of mental computation and math cognition [2], [12–14]. Research studies [6-7] have found out that different style of individual problem-solving strategies may determine the cortical activation during mental calculation, which is shown in Figure 2. Abacus based mental calculation is one of the exclusive strategies from Chinese culture that is used to solve mathematical calculations. During these past few years, several numbers of fMRI studies regarding to abacus-based mental calculation have continuously been conducted [1], [6], [9].

Through fMRI studies[7,9–11], it is reported that an abacus expert can solve complex computations mentally faster and more accurately due to the sequentially organized processes, which is otherwise a time-consuming activity. Time-consuming activity occurs due to the neural processed regions, which is found to be related to visuospatial and visuomotor processing [1]. Thus, this neural process implies that the network is more effectively linked. Other than examining normal subjects under functional MRI while doing arithmetical problem, studies with dyscalculia patient [16] have also been done and it is found that grey matter density inside parietal cortex of these patients was decreased. A dyscalculia patient refers to a person with mathematical disability who has difficulties in understanding numbers, manipulating numbers and learning math facts.

Functional MRI has also been used in studying cognitive strategies that influence the pattern of cortical activation during mental subtraction [6,7,11]. The significant activation of brain regions are shown in Figure 3. From different types of mental calculation operation, subtraction is one of the mathematical operations that is highly performed in our daily routine. Burbaud et al.[8] observed different significant activation areas between visual strategy and verbal strategy. Both strategies discover the significant activation areas of dorsolateral prefrontal cortex and premotor cortex but compared to visual strategy, verbal strategy activate more significant area such as Broca areas (44 and 45), left anterior cingulated cortex and parietal cortex. Through enormous study [3-4,6,9,13-14] of functional MRI on mathematics cognition and mental calculation, it is conjecture that parietal cortex is the crucial areas involved in the brain. This is due to the depiction of numeric quantities inside the brain and an observation of brain activation during calculation. Additionally, a PET study [19] has discovered that the left intraparietal sulcus, which is designated within the parietal lobes is also involved in numerical, quantity manipulation and exact calculation.

Researchers [10] have also discovered that cultural experiences structure the brain function during mathematical problem solving. Rather than culture, individual strategies [6,7,11] give a big influence to the pattern of brain activity. Cantlon et. al[10] have reported that different patterns of brain activity can emerge during mathematical tasks even among individuals from the same culture who share the same language. Qiu et. al verified that Native Chinese Speakers(NCS) manifest a dorsal visuo-pathway compared to Native English Speakers(NES). However, both English and Chinese Speakers activate inferior parietal cortex during mental calculation.

The surrounding environment also plays a crucial role in solving mathematical problems. Therefore, fMRI studies have been done to compare the brain activation of human subjects doing mathematical problems in different environments, which are in a noise condition and in a quiet condition [20]. Aini et al. have verified that performing addition in a noise environments need higher attention and excessive
function of working memory compared with the subject that doing subtraction in the same environment. The bilateral activation in parietal region promotes arithmetic problem solving, while the frontal brain region is involved in the executive process and working memory in mental calculation.

4 Discussion and Conclusion
Numerous studies have concluded that cognitive neuroscientists have proposed a series of tools, methodologies and theories to examine cognitive processes [21] during brain learning activities especially during mathematical thinking. Brain activities are also known as neuron activities. Thus, the growing neural networks of interconnected neurons are crucial to the transmission of information through the brain. The amounts of blood oxygen needed are controlled by the neurons. The changes of blood oxygen level in active regions of the brain may influence the image captured by fMRI. Studies on cognitive brain show that the ability of people to do mathematical thinking can be influenced by various factors. These factors include individual strategies, different native speakers and different arithmetic operations. These factors also influence the significant activation of the brain regions.

There are two types of individual strategies which are verbal strategy and visual strategy [2,4-6-7]. Verbal strategy is defined as when the subjects simplify the calculation using arithmetical principles and fact knowledge, while visual strategy is defined when the subjects establish a procedure of calculation to mentally visualize the operation. On the other hand, a number of studies have proven that different native speaker contributes different significant activation brain area. For example, between English Native Speakers and Chinese Native Speakers, both native speakers’ language is affected by culture. Besides that, they also differ in writing systems, abacus practices, working memory for numbers and preferred mathematical strategies [10].

Therefore, from this review we can summarize that parietal cortex is the crucial brain area involved in mental calculation due to the representation of numeric quantities inside the brain [2,4-5,10-11,18,20]. Besides that, enormous studies related to other brain learning activities using fMRI have been conducted, among others, on the study of attention, reading partial equation and study on schizophrenia patients. Through this enormous research, researchers discover that different brain learning activities will activate different brain area. Therefore, it shows that each of the brain area has its own role in managing human activities. Indeed, through these previous research studies on fMRI, researchers found that brain activity of certain tasks rely on the cooperation of the neural system, which are located in many different parts of the brain.

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