

## EEG Neural Substrates of Cognitive Engagements for Research-Based Learning with Contemplative Education in Young Children

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### Abstract

One becomes aware of the evidence of cognitive insights following attending the research-based learning program with contemplative education, electroencephalography (EEG) and electrodermal activity (EDA) were used to track the improvement of emotional and cognitive states. Research-based learning (RBL) and teaching models were developed to enhance research characteristics and cognitive training for children in the 21<sup>st</sup> century. To date, there have been no reliable cognitive tools to monitor the cognitive insight of the child who attends the course. The EEG, EDA, and cognitive scores of 30 healthy students participating in a research-based program for an hour per week were evaluated prior to the course, 3 and 6 months after the program started. The cognitive tests included a standard progressive matrix (SPM) test, arithmetic test, Eriksen flanker task and biofeedback sessions. The same procedures were determined in the comparative students' group. After 6 months of taking the program, students in the RBL group showed a significant improvement in their SPM and arithmetic test scores. A significant increase in beta and gamma activity was detected in the temporal cortex of the RBL group during the SPM test. A more significant enhancement of frontal theta power was observed during the arithmetic test. This study shows that contemplative education and RBL improve cognitive abilities, indicating a significant increase in EEG quantity for cognitive engagement and the ability to confer individual differences in cognitive abilities.

**Keywords:** Contemplative education, EEG, Research-based learning, Young children, Cognitive development

### Introduction

RBL consists of 3 domains: Contemplative Education (CE), Systematic Thinking (ST) and Professional Learning Community (PLC). CE aims to put the learner and their self-reflective mindfulness at the heart of the teaching and learning process, rather than focusing on measurable outcomes. To help students develop higher intelligence, learning should be promoted in this way to help them understand and realize the value of what they learned. These are processes for coaching and mentoring master teachers (MTs) to coach and facilitate their students for RBL [1]. Obtaining knowledge from this concept involves 3 aspects; profound listening, thoughtful thinking, and seeing as it is the goal to create a fundamental change in the way of thinking, beliefs, and new consciousness about self, the world and things that affect intelligent behavior and lifestyle [2].

Through the use of the research process to explore the subject being studied, learning management emphasizes the importance of the student's knowledge creation for themselves as much as possible. Using RBL management, learners will be able to develop their intellectual abilities, advanced thinking skills in critical reflection, the ability to solve problems using reason, the ability to work with others and the ability to conduct research [3]. Since more interaction occurs between teachers and learners, teachers prepare to teach less since they can make the learners know and understand more. Learning skills empower the learners to learn continuously, research skills enable them to become knowledgeable, and teachers could exchange knowledge with learners. The research-based approach enables the students to not only gain knowledge but also develop the skills to cope with changes in a knowledge-based society. In addition to being independent, students will be able to criticize from an interdisciplinary perspective [4].

Cognitive science is the field of psychological research that investigates scientific studies of the way people think, feel, recollect, reason, disconnect and solve problems while avoiding overlapping concepts such as philosophy that may overlap [5]. There are widespread individual differences in the ability to reason, solve problems and learn, and this leads to human differences in the general ability to cope with challenges. Cognitive skills development refers to the maturing of a variety of abilities and involves the maturation of a broad range of abilities [6]. Skill development is a dynamic process that begins early in life and lays the groundwork for later success [7]. A frontoparietal network is generally implicated in intelligence based on structural and functional neuroimaging studies [8]. The same network is also implicated in perception, memory storage and language functions. It has also been demonstrated that emotion and mental readiness have a significant impact on various cognitive processes in humans, including perception, attention, learning, memory, reasoning and problem-solving [9]. The insula, frontal, anterior/superior and medial temporal, posterior and paracingulate, lateral occipital cortices, thalamic volume, and the white matter microstructure of thalamic and association fibers, and of the forceps minor exhibited unique contributions to intelligence [10]. Along with neuroplastic mechanisms, disengaging 6 weeks from the “real world” in favor of virtual settings may similarly induce adverse neurocognitive changes caused by significant reductions in grey matter within the orbitofrontal cortex - a brain region implicated in impulse control and decision-making [11]. As part of the concept of mental intelligence studies, research brain conceptual learning builds rapport among teachers, learning managers, students, and communities, by listening to each other and learning from each other while using “conversational aesthetics” to foster academic learning within a context of real-life community/social contexts. Student achievement is an important indicator of an educated outcome, however, observed behaviors and academic scores are insufficient to suggest the positive results of a conscience education. The purpose of this study was to examine brain function development of cognitive skills in students participating in contemplative education with a research-based program by collecting EEG data and conducting neurocognitive assessments.

## Materials and methods

### Participants

The participants were included from the specific target group by the selection method of purposive sampling as this study aimed to study the competency development process of early childhood education students studying in research-based courses. A sample of 30 children from the schools who participated in contemplative education with a research-based program was collected in the experiment group. The age range was 9 to 10.5 years old. The age average of the children in the experiment group was 9.8 years old. A comparative group was conducted with 30 students of the same age from nearby schools in similar environments. The age range was 7.7 to 10.4 years old. The age average of the children in the control group was 9.5 years old. All participants were verified healthy with normal vision and right-hand dominance. This study was performed under the principles of the Declaration of Helsinki and approved by the Prince of Songkla University ethics committee (HSc-HREC-63-043-1-1).

### Program intervention

The course was conducted by the academic staff who had expertise in teaching the course for 2 h per week over a 6-month period. The institution where the children receive the course reported that the students had not received a similar course prior to the current study. Schools in the RBL group have identified active teaching activities for the research-based project activity as shown in **Table 1** during the 1<sup>st</sup> semester of the academic year 2022, every Wednesday during the 4<sup>th</sup> and 5<sup>th</sup> periods, and identified the 2 teachers who will lead the project. Lesson plans have been designed for a total of 15 activity procedures based on 4 basic steps consisting of contemplative and moral steps, the concept and knowledge stage, the practical of the new knowledge creation and lessons learned. Throughout activities, students were given the freedom to think and present their thoughts confidently. Teachers acted as mentors and guided them to accomplish. Design and building experiment sessions allow students to brainstorm with 2 - 3 individuals per group to create a research project. Teachers act as coaches to monitor students' progress, and students reflect on their learning.

**Table 1** Lesson plans and procedures of a research-based project.

| Lesson plans                          |  | Procedures                                |                                   |
|---------------------------------------|--|---|-----------------------------------|
| Preparation                           | Know yourself and understand your studies  | Thinking and problem-solving              | STEM with science skills          |
| Skill training                        | Questioning skills                         | Communication skills                      | Interviewing and recording skills |
| Survey                                | Community                                  | Data analysis and preliminary experiments | Create a project topic            |
| Designing and building the experiment | Variables and experiments                  | Variables and experiments                 | Variables and experiments         |
| Data collection and summary           | Analyze and summarize experimental results | The simple summary of knowledge           | Preparing to publish the work     |

### Cognitive evaluation tests

The study protocol was drawn as shown in **Figure 1**. Each session lasts for about 2 min in an air-conditioned room with a temperature of 25 °C and quiet, and children are allowed a few minutes to rest before starting a new session. The test consisted of 3 phases: 2 min eye open focused on the fixation of the screen, 2 min eye closed and cognitive evaluation. The cognitive evaluation included Eriksen flanker, Raven's standard progressive matrix, arithmetic tasks and biofeedback session. The order of the tests was randomized to reduce the effect of late fatigue that might be seen in young participants.

For the Eriksen flanker task, the target is positioned in the center and is flanked by nontarget stimuli. The individual is requested to press the left or right arrow key according to the target's direction. It is called congruent stimuli or compatible mode when the nontarget stimuli are oriented in the same direction as the target, and incongruent stimuli or incompatible mode when the nontarget stimuli are oriented opposite to the target.

SPM test consists of 24 items, with each item becoming progressively more difficult. The SPM presents a series of 2×2 geometric designs with 1 piece missing. The participants must select the correct missing piece from the 5 options correctly and promptly. The SPM score is calculated based on the score multiplied by the amount of time to answer correctly since the stimulus was presented.

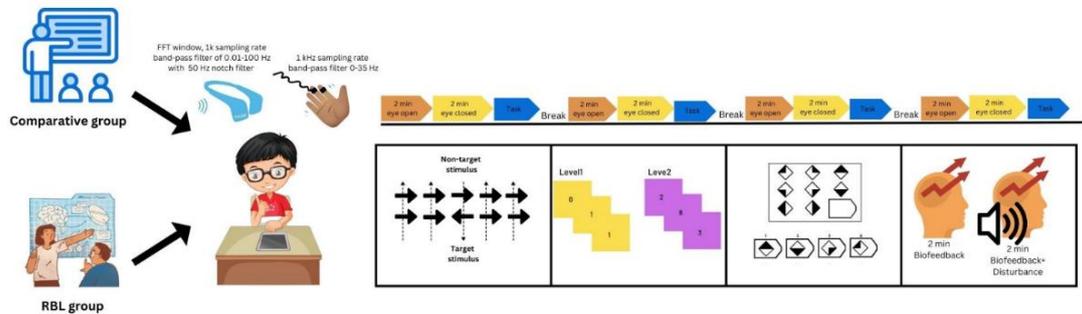
In the arithmetic test, there are 2 levels, each of which contains 15 items. There are 0 and 1 on the item of level 1 and 1 to 9 on the item of level 2. Numbers appear randomly for 3 numbers in each 3 s, and the participant has 30 s to answer the summation. Participants monitored their skin conductance levels on the screen for the 2-minute biofeedback session, and they constantly controlled themselves to keep or increase the tracing levels. There was another audio disturbance 2 min later that they had to control in the same way.

### EEG and EDA acquisition and analysis

Participants sat on the chair with a backrest and recorded EEG using the Muse™ EEG headband while performing the tasks prior to the research project course, 3 and 6 months after the courses [12,13]. Electrodes on the MUSE EEG system are analogous to 2 frontal (AF7 and AF8) and 2 temporals (TP9 and TP10). Fpz serves as the reference electrode. These are named and positioned according to the International 10 - 20 System. The electrode impedance of the device was kept lower than 5 kΩ, the sampling rate was digitized at 1 kHz, and a band-pass filter of 0.01 - 100 Hz was used. A 50 Hz notch filter was applied to eliminate power line artifacts. Brainwave amplitudes for delta (1 - 4 Hz), theta (4 - 8 Hz), alpha (8 - 12 Hz), beta (12 - 20 Hz), and gamma (30 - 50 Hz) were measured in decibels (dB). Data was sent to the Mind Monitor app to compute their power spectral density (PSD) using a Hanning window cosine with 50 % window overlap and 1,024 FFT size. EEG powers from 2 specific electrodes were averaged for the frontal region and temporal region. The relative change of the EEG band was expressed as a proportion to the open-eye period as shown in the formula below. In cases of electrode artifacts, the electrodes were adjusted, and the recording session restarted.

$$\text{Relative change of EEG/EDA} = ((\text{Test} - \text{Eye opened}) / ((\text{Test} + \text{Eye opened}))). \quad (1)$$

EDA activity signals were measured by BIOPAC MP36 data acquisition hardware with a 2,000 Hz sampling rate. Along with Biopac Student laboratory software, SS57LA electrode leads were placed on the index and middle fingers of the non-dominant hand. The EDA measured skin conductance between 2 silver-coated electrodes with a 35 Hz sampling frequency. Maximal skin conductance values were analyzed in each session as relative change calculated according to the same relative change of EEG.



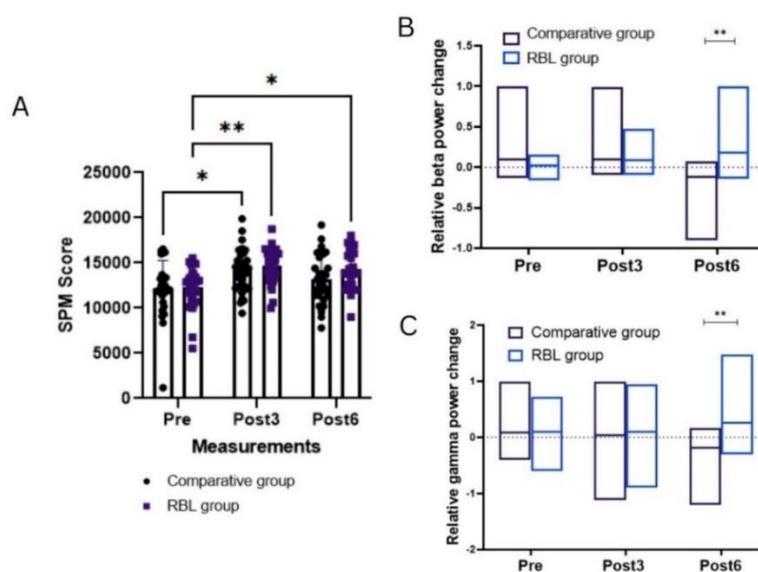
**Figure 1** Study paradigm.

### Statistical analysis

All data were expressed as the mean  $\pm$  SEM. The behavioral and electrosignal data were analyzed by using the open-source software Jamovi Version 2.4.1.1. Two-way ANOVA and Tukey post hoc test were used to determine the significant effect of the treatment and recording sessions.

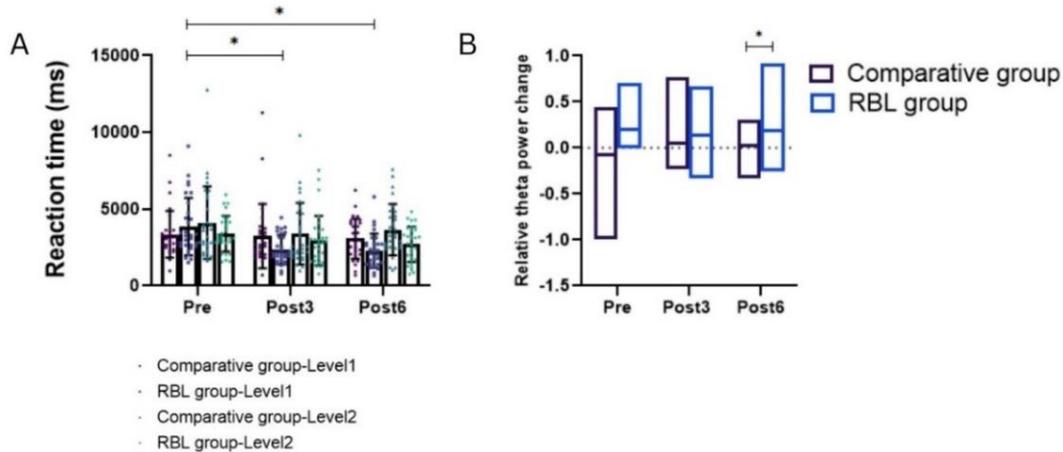
### Results and discussion

Analyses of EEG determinations and autonomic nervous system responses were conducted on RBL education. The significant effect of RBL and time taken to the course on the SPM task ( $F(2,274) = 12.52$ ,  $p < 0.001$ ) was analyzed by 2-way ANOVA. Students taking the course showed a significantly higher SPM score after 3 months ( $p = 0.0029$ ) and 6 months ( $p = 0.015$ ) as shown in **Figure 2**. For the control group, the significant change was found after 3 months from prior recording, but not after 6 months. This effect was compared to the prior score before taking the class. The effect of the course showed the influence on EEG brain activity at the temporal brain region with the specific frequency ranges in the beta ( $F(2,100) = 6.414$ ,  $p = 0.0024$ ) and gamma ( $F(2,100) = 3.475$ ,  $p = 0.0348$ ) ranges. Relative change of beta ( $p = 0.0032$ ) and gamma ( $p = 0.0089$ ) bands during performing SPM tasks were significantly increased in students who took the course for 6 months in comparison to the comparative group.



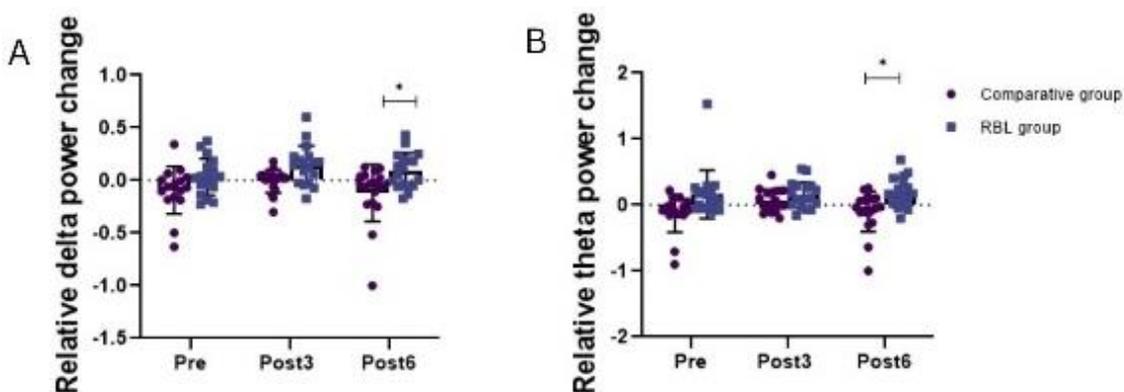
**Figure 2** (A) SPM scores, (B) temporal beta, and (C) gamma brain activities while performing the SPM task.

Two-way ANOVA also revealed the influences of time taking the course on arithmetic reaction time ( $F(2,348) = 7.837, p = 0.0005$ ). **Figure 3** shows the reaction time to answer the simple arithmetic questions in level 1 of students who took the course spent more speed in the 3 months ( $p = 0.0211$ ) and 6 months ( $p = 0.0126$ ) in comparison to the prior recording. The influence of the course and time taken was significant to the frontal EEG brain activity during arithmetic tasks ( $F(1.98) = 12.16, p = 0.0007$ ). Theta activity was significantly higher in students who took the course at the 6 months ( $p = 0.0089$ ) in comparison to the comparative group. No significant change was observed in the temporal cortex.



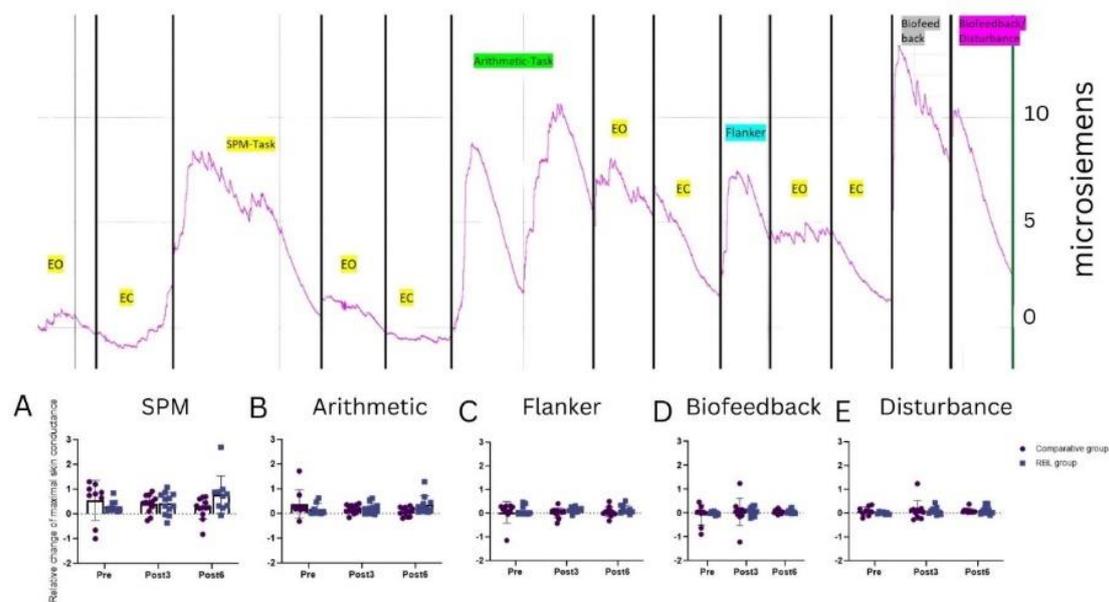
**Figure 3** (A) Reaction time and (B) anterior frontal theta brain activities during performing the arithmetic task.

The course was also statistically found to be influential on the ability to control themselves according to frontal EEG brain activity ( $F(1,100) = 18.71, p < 0.0001$ ). **Figure 4** shows students who took the course for 6 months had high activity on delta frequency ( $p = 0.019$ ) in comparison to the comparative group. The same pattern was found in the effect of the audio disturbance during biofeedback ( $F(1,100) = 17.76, p < 0.0001$ ). Students who took the course for 6 months had higher theta frontal activity ( $p = 0.0219$ ) when compared to the comparative group.



**Figure 4** (A) EEG delta brain activities at the temporal cortex during performing biofeedback and (B) EEG theta brain activities at the frontal cortex during auditory disturbance biofeedback.

Changes in the skin conductance level (SCL) reflect an increase or decrease in autonomic arousal, and there is a 2<sup>nd</sup> component known as the phasic component that refers to the signal elements that change quickly, the Skin Conductance Response (SCR). In the representative EDA recording shown in the upper of **Figure 5**, the SCL dropped when the eyes were closed, and then spiked when the tasks were performed, and the ANOVA analysis revealed no significant differences in relative EDA of the tasks between the groups.



**Figure 5** EDA tracing among phases during recording sessions. (A) relative change of maximal skin conductance value during pre-, post-3 and post-6 months of the course starting in SPM test, (B) arithmetic task, (C) Eriksen flanker, (D) biofeedback, and (E) biofeedback with audio-disturbance.

The concept of cognition is much more complex than what we usually consider it to be, and intelligence is a more finely tuned concept of cognition. There have been numerous psychological constructs analyzed as predictors of academic success over the past century, and they have been relevant for more than a century [14-16]. It has been shown that academic achievement is heavily influenced by the functioning of basic cognitive processes, such as a person's ability to process information, their working memory ability and their sense of numbers [17-21]. Higher-order cognitive abilities are determined by the accuracy and speed of information processing [22]. In direct perception, the visuospatial working memory is responsible for storing and processing visual information related to spatial location and visual stimuli [23,24]. Furthermore, visual working memory is also critical for success in a variety of scientific disciplines, from mother-tongue acquisition to mathematics, including basic arithmetic and geometric calculations, as well as spatial relationships [15,25].

Using Raven's standard progressive matrices test or progressive test, individuals are assessed for their ability to reason and solve problems without extensive reliance on declarative knowledge from schooling or previous experience [26]. Consequently, the significant increase in gamma and beta activity in the temporal cortex of the RBL group after 3 and 6 months of taking the program points to development in fluid intelligence which reflects the individual's clear-thinking ability, and spatial and logical skills. There is a strong correlation between cognitive processes and integral outputs in the temporal brain regions, in particular learning and memory, involving fast and flexible dynamic coordination and information gating. The hippocampus (HPC) is a structure of the temporal lobe extensively studied in spatial cognition where information is selectively processed using beta and gamma oscillations to shape cognitive behavior. The window of opportunity of the gamma cycle corresponds to the cell assembly lifetime. When multiple objects must be kept in mind during working memory tasks, 1 object is coded by a gamma cycle nested within 1 theta cycle. As a result of inhibition in GABAergic transmission, hippocampal gamma is activated and cognitive performance is improved [27]. The research found that emotion recognition using EEG was positive in gamma band distribution in the lateral temporal lobe (roughly 30 to 50 Hz) [28]. As part of the retrieval and formation of memory, perceptual attention, decision-making, and manipulation, the angular gyrus (AG) has extensive connections with the medial temporal lobe, precuneus, dorsolateral prefrontal cortex, and superior parietal lobe. The use of 40-Hz high-frequency repetitive transcranial magnetic stimulation (rTMS) over the bilateral angular gyrus in patients with probable Alzheimer's disease shows that modulating gamma-band oscillations improves cognitive function, improving long-range, dynamic, and local brain connectivity [29]. Increasing the EEG rhythm indicates heightened brain activity and higher

consciousness degrees [30]. This core node can facilitate the integration of information across cognitive domains [31,32].

A distributed brain network called the default mode network (DMN) is responsible for cognition, including episodic memory and internal thought monitoring. It is composed of a diverse set of brain regions, including the posterior cingulate cortex, the medial prefrontal cortex, the angular gyrus, the anterior prefrontal cortex, the lateral temporal cortex, and the medial temporal lobe (MTL). A slow-wave (< 4 Hz) synchronization dominates intra-DMN connectivity, and Beta synchronization dominates cross-DMN interactions [33]. The slow delta activity in the temporal lobe indicated the involvement in the brain process of emotional control and coordination on inhibition of the sensory afferents. Therefore, the decrease in delta power activity in the temporal cortex of the comparative group during 3<sup>rd</sup> recording suggests that doing the test repeatedly is generally boring for them, which results in a limited attention span and lack of interest in what is occurring repeatedly. This effect was not observed for students in the RBL group.

An indicator of success in mathematics learning from primary to high school is the ability to estimate the number of objects without directly counting them [34]. Arithmetic proficiency is mediated by fact retrieval and calculation since prior knowledge facilitates fast access to learned arithmetic facts [35]. Speed and accuracy of performance are also affected by attentional resources, sequencing mental operations and decision-making. Moreover, resources for working memory (i.e., storing and manipulating information temporarily) are needed when it is difficult to retrieve results and they need to be calculated based on decomposition rules and other criteria. In order to retrieve learned facts and perform more elaborate calculations, when necessary, the prefrontal cortex is responsible for decision-making, sequencing and working memory. Theta increases in them with the workload associated with numerous processes including working memory, problem-solving, encoding, or self-monitoring and representing the dynamic functional binding of widely distributed cortical assemblies, essential for cognitive processing. The frontal lobe (reasoning center) is intertwined with the posterior parietal lobe, occipital lobe and temporal lobe with the midbrain to pursue and accomplish neuroplasticity and learning [36]. Lower frontal theta activity was observed in the boredom condition, indicating a lack of cognitive control [37]. Thereafter, the higher speed to answer in the arithmetic task level 1 of RBL students suggests an achievement process via visual sensory, retrieval memory, numeric integration and decision-making. In addition to that, theta activity in the frontal areas was higher in the 3<sup>rd</sup> recording, whereas frontal theta dropped in the comparative group.

## Conclusions

Putting together, research-based project classroom activities could develop fluid intelligence, mathematic learning, and cognitive self-control. The maintaining beta and gamma activity in the temporal cortex during the SPM task, frontal theta during the arithmetic task and temporal delta power during biofeedback including frontal theta activity during audio disturbance confirms the engagement of the brain to succeed in cognitive learning. Because the course was assigned once a week to students, this RBL course must be strengthened more than once a week to maintain high performance over time. The study of brain-behavior relations can be evaluated by using multiple methodologies, and EEG is a relatively simple and inexpensive approach to examining relationships during development.

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## References

- [1] W Rattanaprom. Failure of research-based learning implementation in basic education. *Int. Educ. Stud.* 2019; **12**, 19-23.
- [2] D Chongcharoen and P Weerpiput. The effects of learning management using contemplative education, coaching system and research-based learning process to competency development of students in early childhood education program. *Turk. Online J. Qual. Inq.* 2021; **12**, 10775-86.
- [3] J Noonchart. The research and development of teacher production and training system on teaching biology through contemplative education coaching & mentoring system and research-based learning. *Solid State Tech.* 2021; **64**, 5748-58.
- [4] L Newman. Bodies of knowledge: Historians, health and education. *Hist. Educ.* 2023; **52**, 479-94.

- [5] RK Sari, A Sutiadiningsih, H Zaini, F Meisarah and AA Hubur. Factors affecting cognitive intelligence theory. *J. Crit. Rev.* 2020; **7**, 402-10.
- [6] IFVD Bos, EH Kroesbergen, JEV Luit, I Xenidou-Dervou, LM Jonkman, MVD Schoot and ECDMV Lieshout. Longitudinal development of number line estimation and mathematics performance in primary school children. *J. Exp. Child Psychol.* 2015; **134**, 12-29.
- [7] T Kautz, JJ Heckman, R Diris, BT Weel and L Borghans. Fostering and measuring skills: Improving cognitive and non-cognitive skills to promote lifetime success. *OECD Educ. Work. Paper.* 2014, <https://doi.org/10.1787/5jxsr7vr78f7-en>.
- [8] R Colom, S Karama, RE Jung and RJ Haier. Human intelligence and brain networks. *Dialogues Clin. Neurosci.* 2010; **12**, 489-501.
- [9] CM Tyng, HU Amin, MNM Saad and AS Malik. The influences of emotion on learning and memory. *Front. Psychol.* 2017; **8**, 1454.
- [10] SR Cox, SJ Ritchie, C Fawns-Ritchie, EM Tucker-Drob and IJ Deary. Structural brain imaging correlates of general intelligence in UK Biobank. *Intelligence* 2019; **76**, 101376.
- [11] F Zhou, C Montag, R Sariyska, B Lachmann, M Reuter, B Weber, P Trautner, KM Kendrick, S Markett and B Becker. Orbitofrontal gray matter deficits as marker of Internet gaming disorder: Converging evidence from a cross-sectional and prospective longitudinal design. *Addiction Biol.* 2019; **24**, 100-9.
- [12] OE Krigolson, CC Williams, A Norton, CD Hassall and FL Colino. Choosing MUSE: Validation of a low-cost, portable EEG system for ERP research. *Front. Neurosci.* 2017; **11**, 109.
- [13] E Ratti, S Waninger, C Berka, G Ruffini and A Verma. Comparison of medical and consumer wireless EEG systems for use in clinical trials. *Front. Hum. Neurosci.* 2017; **11**, 398.
- [14] IJ Deary, S Strand, P Smith and C Fernandes. Intelligence and educational achievement. *Intelligence* 2007; **35**, 13-21.
- [15] LA Verbitskaya, YP Zinchenko, SB Malykh, IV Gaidamashko, OA Kalmyk and TN Tikhomirova. Cognitive predictors of success in learning Russian among native speakers of high school age in different educational systems. *Psychol. Russia State Art* 2020; **13**, 2-15.
- [16] T Tikhomirova, A Malykh and S Malykh. Predicting academic achievement with cognitive abilities: Cross-sectional study across school education. *Behav. Sci.* 2020; **10**, 158.
- [17] LA Verbitskaya, S Malykh and T Tikhomirova. Cognitive predictors of success in learning Russian in native and non-native speakers at high school age. *Procedia Soc. Behav. Sci.* 2017; **237**, 1236-41.
- [18] D Luo, LA Thompson and DK Detterman. The criterion validity of tasks of basic cognitive processes. *Intelligence* 2006; **34**, 79-120.
- [19] M Rodic, X Zhou, T Tikhomirova, W Wei, S Malykh, V Ismatulina, E Sabirova, Y Davidova, MG Tosto, JP Lemelin and Y Kovas. Cross-cultural investigation into cognitive underpinnings of individual differences in early arithmetic. *Dev. Sci.* 2015; **18**, 165-74.
- [20] T Tikhomirova, Y Kuzmina, I Lysenkova and S Malykh. Development of approximate number sense across the elementary school years: A cross-cultural longitudinal study. *Dev Sci.* 2019; **22**, e12823.
- [21] K Laidra, H Pullmann and J Allik. Personality and intelligence as predictors of academic achievement: A cross-sectional study from elementary to secondary school. *Pers. Individ. Differ.* 2007; **42**, 441-51.
- [22] LA Brown, JR Brockmole, AJ Gow and IJ Deary. Processing speed and visuospatial executive function predict visual working memory ability in older adults. *Exp. Aging Res.* 2012; **38**, 1-19.
- [23] T Tikhomirova. Spatial thinking and memory in Russian high school students with different levels of mathematical fluency. *Procedia Soc. Behav. Sci.* 2017; **237**, 1260-4.
- [24] R Bull, KA Espy and SA Wiebe. Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Dev. Neuropsychol.* 2008; **33**, 205-28.
- [25] SVD Sluis, AVD Leij and PFD Jong. Working memory in Dutch children with reading-and arithmetic-related LD. *J. Learn. Disabil.* 2005; **38**, 207-21.
- [26] W Yang, P Liu, D Wei, W Li, G Hitchman, X Li, J Qiu and Q Zhang. Females and males rely on different cortical regions in raven's matrices reasoning capacity: Evidence from a voxel-based morphometry study. *PLoS One* 2014; **9**, e93104.
- [27] V Wespatat, F Tennigkeit and W Singer. Phase sensitivity of synaptic modifications in oscillating cells of rat visual cortex. *J. Neurosci.* 2004; **24**, 9067-75.
- [28] S Issa, Q Peng and X You. Emotion classification using EEG brain signals and the broad learning system. *IEEE Trans. Syst. Man Cybern. Syst.* 2020; **51**, 7382-91.

- [29] C Liu, T Han, Z Xu, J Liu, M Zhang, J Du, Q Zhou, Y Duan, Y Li, J Wang, D Cui and Y Wang. Modulating gamma oscillations promotes brain connectivity to improve cognitive impairment. *Cerebr. Cortex* 2022; **32**, 2644-56.
- [30] M Roohi-Azizi, L Azimi, S Heysieattalab and M Aamidfar. Changes of the brain's bioelectrical activity in cognition, consciousness, and some mental disorders. *Med. J. Islam. Republic Iran* 2017; **31**, 53.
- [31] C Sestieri, GL Shulman and M Corbetta. The contribution of the human posterior parietal cortex to episodic memory. *Nat. Rev. Neurosci.* 2017; **18**, 183-92.
- [32] MD Fox, RL Buckner, H Liu, MM Chakravarty, AM Lozano and A Pascual-Leone. Resting-state networks link invasive and noninvasive brain stimulation across diverse psychiatric and neurological diseases. *Proc. Natl. Acad. Sci.* 2014; **111**, E4367-E4375.
- [33] A Das, CDL Angeles and V Menon. Electrophysiological foundations of the human default-mode network revealed by intracranial-EEG recordings during resting-state and cognition. *NeuroImage* 2022; **250**, 118927.
- [34] TN Tikhomirova, SB Malykh, MG Tosto and Y Kovas. Cognitive characteristics and mathematical achievement in high school students: Cross-cultural analyses. *Psikhologicheskii Zhurnal* 2014; **35**, 41-53.
- [35] V Menon. Developmental cognitive neuroscience of arithmetic: Implications for learning and education. *ZDM* 2010; **42**, 515-25.
- [36] S Chattopadhyay. An interactive model of relevance, cognitive load, spatial memory, ADHD, and EEG, Available at: <https://osf.io/preprints/psyarxiv/smwka>, accessed May 2023.
- [37] K Katahira, Y Yamazaki, C Yamaoka, H Ozaki, S Nakagawa and N Nagata. EEG correlates of the flow state: A combination of increased frontal theta and moderate frontocentral alpha rhythm in the mental arithmetic task. *Front. Psychol.* 2018; **9**, 300.