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Multisensory Instruction and Beta Oscillations Modification in Vocabulary Retention at Pre-school Level: A QEEG Study

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Abstract To investigate the impact of the multisensory method at the pre-school level, this study employed beta-waves during vocabulary retention. Six EFL learners were assigned to two groups: non-multisensory and multisensory. The comparison of the results of pre- and post-brain records denoted no significant differences in beta frequency ranges between the groups. A significant correlation was found between learners' mean score on the post-test and the increase in beta wave-frequencies on Fp1-Fp2-regions at post-records in the multisensory-group; however, the case study analysis showed decreases in beta1 wave frequencies in the non-multisensory-group. The topography-inspections demonstrated increases in high-beta-wave frequencies in the prefrontal cortex in both groups and activity localization on the para-hippocampal in the multisensory post-records. The statistical results of non-parametric tests on groups' mean scores revealed no significant difference between experimental and control groups. The study concluded the promising role of multisensory teaching to improve retention at the pre-school level.

Keywords: *Beta Waves, Foreign Language Vocabulary Retention, Multisensory Teaching, QEEG, Short-Term Memory*

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1. Introduction

The technical architecture of the brain and its mechanisms to process information facilitate the integration and incorporation of multisensory information. When the multitude of multisensory inputs is received by different sensory organs, the perceptual, cognitive, and motor systems decode, integrate, encode, and segregate the information so that the input is perceived as a coherent perceptual representation (Murray et al., 2016). This multisensory processing is essential to learn and live (Williamson, 2011).

The multisensory approach to teaching and learning accentuates delivering all information via sensory modalities: tactile, visual, and auditory. Multisensory teaching subsumes more than just two skills of reading and listening. Instead, it intrigues the learners with the material in more than one way. In almost every multisensory teaching, all learners' senses (touch, taste, smell, hearing, movement, and sight) will be applied. The multisensory method of teaching is useful for all students (Fernald, 1943; Gillingham & Stillman, 1997).

This study aims to analyze beta power band measures in short-term retention of foreign language vocabulary at the pre-school level. In particular, by applying and comparing QEEG data between the multisensory and non-multisensory teaching groups, it aims to objectively and empirically examine the impact of these different methods on short-term vocabulary retention in the participants.

The important issue that distinguishes this study from the others in the field is that they employ neuroimaging during task performance (Such as Ghetti & Bulge, 2012; Hsu et al., 2017), while this study used two QEEG records (pre- and post-records) to check the probable permanent or contemporary influence of the instruction on the brain waves and activities.

This study tries to answer these questions:

Q1. Is there any significant difference between beta wave frequencies (B1, high beta, and beta) on frontal regions (Fp1, Fp2, F3, and F4) in pre- and post-brain records?

Q2. Is there any significant difference between the scores in the post-tests in the multisensory and non-multisensory groups?

Q3. Is there any significant correlation between beta wave frequencies on post-records and scores on the post-test in both groups (multisensory and non-multisensory groups)?

2. Review of Literature

2.1. Multisensory learning and teaching

Multisensory teaching involves engaging learners through more than one sensory modality simultaneously. Research in elementary education highlights the importance of incorporating multisensory instructional strategies to enhance engagement and learning outcomes (Rains et al., 2008). These approaches are particularly effective because they provide multiple pathways for information processing and retention (Morgan, 2019).

Manipulative materials play a central role in multisensory instruction. Rains et al. (2008) describe manipulatives as objects that learners can touch, move, and physically interact with during instruction. Similarly, Chester et al. (1991, as cited in Rains et al., 2008) define manipulatives as materials that learners can manipulate physically or mentally to solve problems. Such materials increase sensory engagement and promote deeper cognitive processing.

Empirical studies have demonstrated the effectiveness of multisensory instruction. For example, Syahputri (2019) reported significant improvements in reading comprehension achievement among learners exposed to multisensory teaching methods. Integrating learners' prior sensory experiences with new instructional content has also been shown to enhance vocabulary acquisition and retention (Griva & Chostelidou, 2013).

2.2. Vocabulary learning and memory systems

Vocabulary learning primarily relies on conscious, explicit memory processes, including declarative, episodic, and semantic memory systems (Takashima et al., 2017). Research indicates that verbal short-term memory plays a critical role in vocabulary acquisition, while verbal working memory is more closely associated with grammar learning (Adams & Gathercole, 2000; Baddeley et al., 1998; French & O'Brien, 2008; Gathercole & Masoura, 2005).

Short-term memory enables the temporary storage and recall of information over brief periods, typically lasting up to approximately 20 minutes (Pinker, 2004). It supports the retention of recently encountered information and is primarily associated with activity in the frontal regions of the cerebral cortex (Norris, 2017).

2.3. Neurobiological basis of memory formation

Learning and retention processes are underpinned by neurobiological changes in the brain. Memory formation involves synaptic modifications that strengthen neural connections, increasing the likelihood of information storage and retrieval (Baddeley et al., 2011). These neural changes can occur over short or long time scales, corresponding to short-term and long-term memory processes (Baddeley, 1992; Goldman-Rakic, 2011).

Chemical changes at the neuronal level contribute to memory consolidation (Guyton & Hall, 2006). Understanding these mechanisms allows researchers to examine how external stimuli, such as instructional methods, affect memory formation and cognitive performance (Norris, 2017).

2.4. Neuroimaging, QEEG, and learning

Advancements in functional neuroimaging have enabled more precise examination of the neural basis of memory and learning. Memory representations are distributed across interconnected brain regions, with short-term memory relying heavily on the prefrontal cortex (Norris, 2017; Tian et al., 2018). Prefrontal regions support the ability to maintain, manipulate, and retrieve information for ongoing cognitive tasks (Guyton & Hall, 2006).

Quantitative electroencephalography (QEEG) provides an indirect measure of neuronal activity by recording and analyzing brainwave patterns. Unlike traditional EEG approaches that focus on identifying abnormalities, QEEG often examines normative brainwave activity to assess cognitive functioning and predict learning outcomes (Marcuse et al., 2015).

2.5. Beta brainwaves, attention, and learning

Cognitive performance and learning are closely associated with beta brainwave activity. Beta waves are linked to focused attention, intentional processing, reasoning, and problem-solving (Demos, 2005; Güntekin et al., 2013; Wróbel, 2000). Beta activity predominates during alert, task-oriented mental states requiring logical thinking and sustained attention (Demos, 2005).

Beta waves are typically divided into three frequency bands: beta 1 (12–15 Hz), beta 2 (15–22 Hz), and high beta or beta 3 (22–38 Hz). Beta 1 is associated with calm focus and intentional processing, beta 2 with active thinking and sustained attention, and high beta with complex cognition, hypervigilance, and anxiety (Demos, 2005). While moderate beta activity supports learning and retention, excessively high beta activity has been associated with reduced attention and poorer learning outcomes (Chiu et al., 2006; Ghetti & Alexander, 2004).

The reliability of EEG measures has been supported by previous research. McEvoy et al. (2000) demonstrated high test–retest reliability for EEG recordings across multiple time intervals, suggesting that resting-state EEG can reliably reflect cognitive changes over time.

3. Method

3.1. Participants

Six preschool novice language learners aged 5 to 6 years old (Mean age: 5.5, two boys and four girls) volunteered to take part in the study. Their mother tongue was Persian, and all were right-handed. One benefit of studying children at this relatively young age, compared with adults, is their neural plasticity (Wong et al., 2012). Participants were randomly assigned to one of the teaching groups: multisensory and non-multisensory, with each group including two girls and one boy. The study was carried out in an underprivileged area of Mashhad, Iran. Data from the questionnaires indicated that the children had no prior experience with English, had not attended English classes, and had never traveled to English-speaking countries.

All participants had normal brain states and no known neurological impairments. Their parents volunteered to participate in the project and provided informed consent approved by the Human Research Ethics Board at Payame-Noor University of Tehran. The study followed ethical standards, and the data were confidential, without mentioning the names of the participants.

The participants' parents filled out a researcher-made background questionnaire, including some related demographic information, such as the parents' educational level, the students' probable participation in FL classes, and their exposure to English because of international travel.

Since the parents were unfamiliar with the QEEG, before taking the records, the researcher (teacher) described and demonstrated the device and the process. They were informed that the device would record brain waves without exposing the children to radiation. The volunteer parents signed the questionnaire and expressed their agreement with their children's participation in the study. The limited number of participants was due to the manageability of the study in terms of the project cost, which any university or institute did not finance.

3.2. Materials and instrumentation

3.2.1. Teaching materials

Ten selected new words (*crayons, ice-cream, tea, hot, cold, wool, bag, glass, flowers, glue*) were presented using manipulatives in a 30-minute session to engage gustatory, olfactory, visual, vestibular, tactile, and auditory senses. The words were selected randomly from the list of vocabulary items presented in the designed Expressive One-word Picture Matching Test (EWPMT).

3.2.2. Expressive One-word Picture Matching Test (EWPMT)

To examine the effect of the treatment, an English test was designed and administered twice, once at the beginning of the study and then after a teaching session, as a pre- and post-test, in both multisensory and non-multisensory groups. Since the purpose of this study was to assess FL vocabulary items retention, the target vocabulary items for the teacher-made test were selected from the vocabulary items to be taught. The EWPMT was designed according to the Expressive One-word Picture Vocabulary Test (Martin & Brownell, 2011). The test is suitable for children aged 2 to 18 years old, and it examines the child's English-speaking vocabulary at various levels of difficulty associated with age.

The EWPMT in this was a 40-item test to be circled by the participants after the teacher's articulation. It took 20 minutes, and one point was assigned for each item on the test. The test reliability was calculated using Cronbach's alpha (alpha = 0.74).

3.2.3. Instruments (QEEG Records)

The QEEG data were recorded using the Mitsar-EEG-201 device (FDA 510K K143233). It incorporates 21 shielded silver-chloride electrodes placed on the scalp in accordance with the 10–20 international system. The EEG sampling rate was kept at 500Hz.

Fp1, Fp2, F3, and F4 electrodes can exhibit EEG activity more typical of prefrontal and some frontal activities (Marcuse et al., 2016). Following some studies in the literature (Guyton & Hall, 2006; Llamas-Alonso et al., 2019), in the present study, the beta, beta1, and high beta frequencies from Fp1, Fp2, F3, and F4 areas and theta/beta ratio power from Fz, Pz, and Cz were analyzed.

3.3. Procedure

The study included one 30-minute session of instruction with six participants (two girls and a boy in each group). The selected new words were presented to both groups under study (multisensory and non-multisensory teaching groups). Before the instruction, there was a QEEG record (pre-record) and a pre-test. Next, after 30 minutes of instruction, there was a post-test and a post-QEEG record. In the recording sessions, the subjects were instructed to keep still. The QEEG data included 5 minutes of open-eyed and 5 minutes of closed-eyed records. The teacher (one of the researchers) was present in all the recording sessions.

In the multisensory method group, real manipulatives were used, and the participants touched, saw, and sometimes smelled and tasted the real objects while they were familiarizing themselves with their meanings. Sometimes they participated in vestibular practices or hands-on activities to learn a new word.

In the multisensory group, real manipulatives were used, and the participants saw, touched, and sometimes smelled and tasted the real objects while they were familiarizing themselves with their meanings. Sometimes they participated in vestibular practices or hands-on activities to learn a new word. In contrast, in the non-multisensory group, the vocabulary items were presented using flashcards while their meaning was explained in Persian.

4. Results

Due to the small sample size (n=3 in each group) and non-normal distribution of the data, the nonparametric tests of Wilcoxon, Mann-Whitney, and Kendall's tau non-categorical tests were applied to scrutinize the data (Soleimani, 2009).

Table 1. Wilcoxon results regarding pre- and post-records of the short-term multisensory and non-multisensory groups on beta and beta1 frequency ranges

Variable		Multisensory		Non-multisensory	
		Pre-record		Post-record	
		Z	Sig	Z	Sig
Beta	FP1	-1.60	0.10	0.00	1.00
	FP2	-1.60	0.10	0.00	1.00
	F3	-1.60	0.10	-0.53	0.59
	F4	-1.60	0.10	-0.53	0.59
Beta1	FP1	-1.60	0.10	-0.53	0.59
	FP2	-1.60	0.10	0.00	1.00
	F3	-1.06	0.28	0.00	1.00
	F4	-1.60	0.10	-0.53	0.59

The nonparametric Wilcoxon signed-rank test was applied to the mean absolute power of the beta and beta1 (SMR) wave frequencies at Fp1, Fp2, F3, and F4 brain regions to assess changes in these wave oscillations after 30 minutes of instruction. The comparison of the QEEG pre- and post-records of the three participants in both multisensory and non-multisensory groups indicated no significant differences (Table 1).

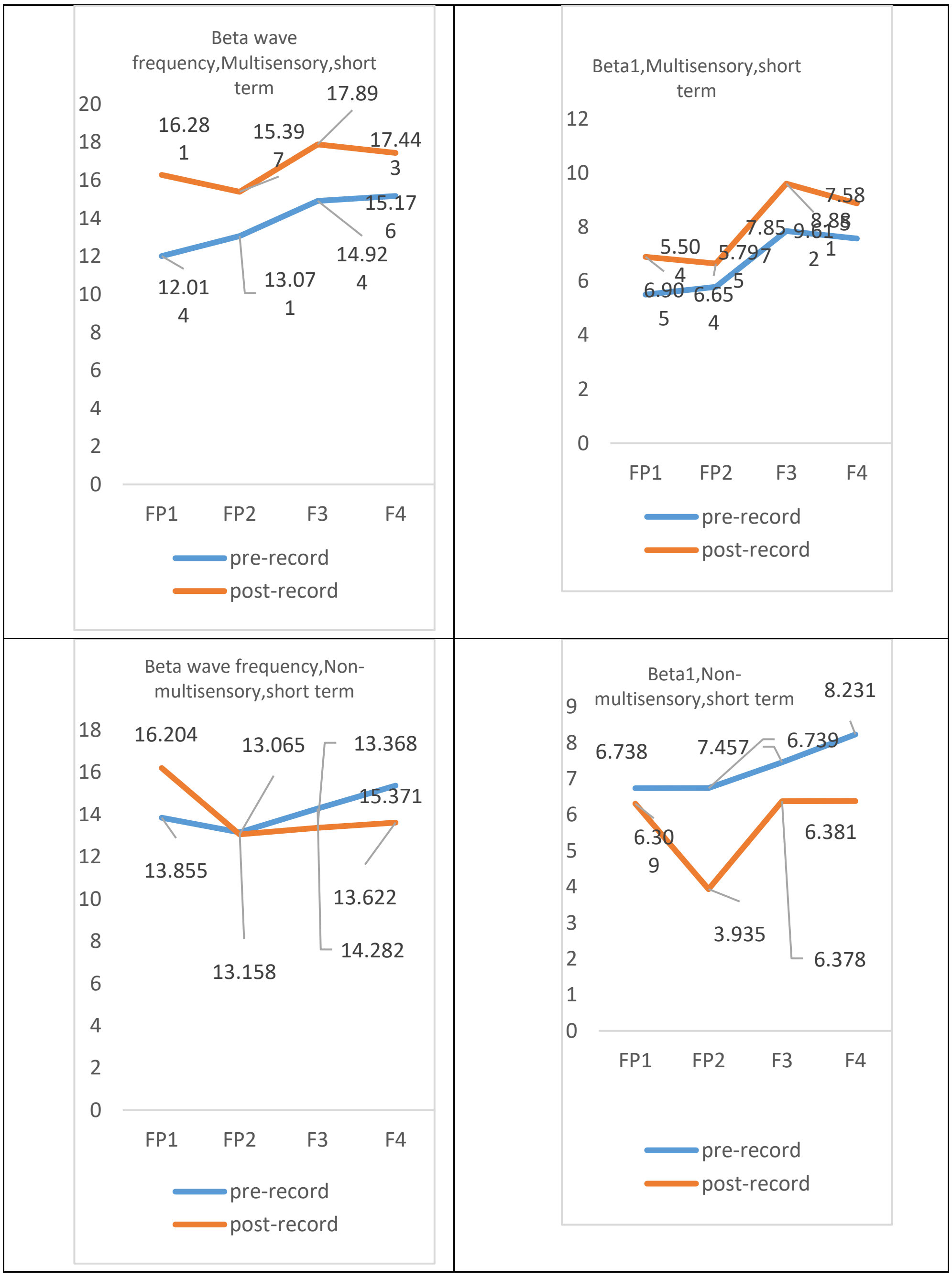

Figure 1. Beta and beta1 frequency band ranges on F3, F4, Fp1, and Fp2 in QEEG pre- and post-records of the multisensory and non-multisensory groups at short-term retention

Though Beta and Beta1 frequencies increased in the multisensory group's post records, the differences were not statistically significant (Figure 1).

The brain maps investigations demonstrated changes in brain activity before and after instruction, which were not statistically significant (Figure 2).

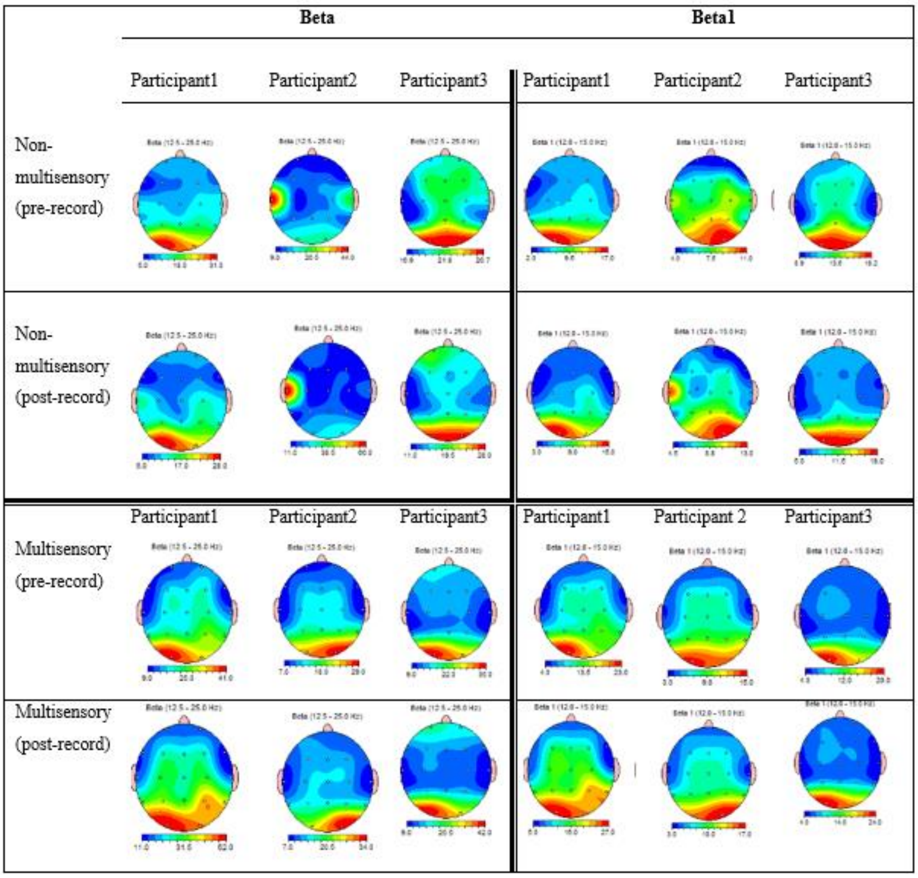

Figure 2. QEEG brain maps record related to beta and beta1 waves before and after 30 minutes of instruction (multisensory and non-multisensory teaching) in the short-term retention phase (Green - Normal Red = Excessive Blue = Diminished Activity)

As shown in Figure 2, the beta and beta1 wave frequencies in prefrontal regions indicated higher activity in the multisensory group's post-records compared to the pre-records and the non-multisensory group's post-records.

QEEG pre- and post-records of the three FL participants in both multisensory and non-multisensory short-term groups were analyzed, using the Wilcoxon non-parametric test. The probable differences in high beta absolute power frequencies at Fp1, Fp2, F3, and F4 were examined, and the results (p > 0.05) indicated no significant differences (Table 2).

Table 2. Wilcoxon results regarding pre- and post-records of the short-term multisensory and non-multisensory groups on high beta frequency ranges

Variable		Multisensory		Non-multisensory	
		Pre-record		Post-record	
		Z	Sig	Z	Sig
High beta	FP1	-1.60	0.10	-1.06	0.28
	FP2	0.00	1.00	-1.60	0.10
	F3	-1.06	0.28	-1.06	0.28
	F4	-1.60	0.10	-0.53	0.59

High beta wave frequencies increased at individual post-records in both groups in comparison to the pre-records. However, the differences were not statistically significant (Figure 3).

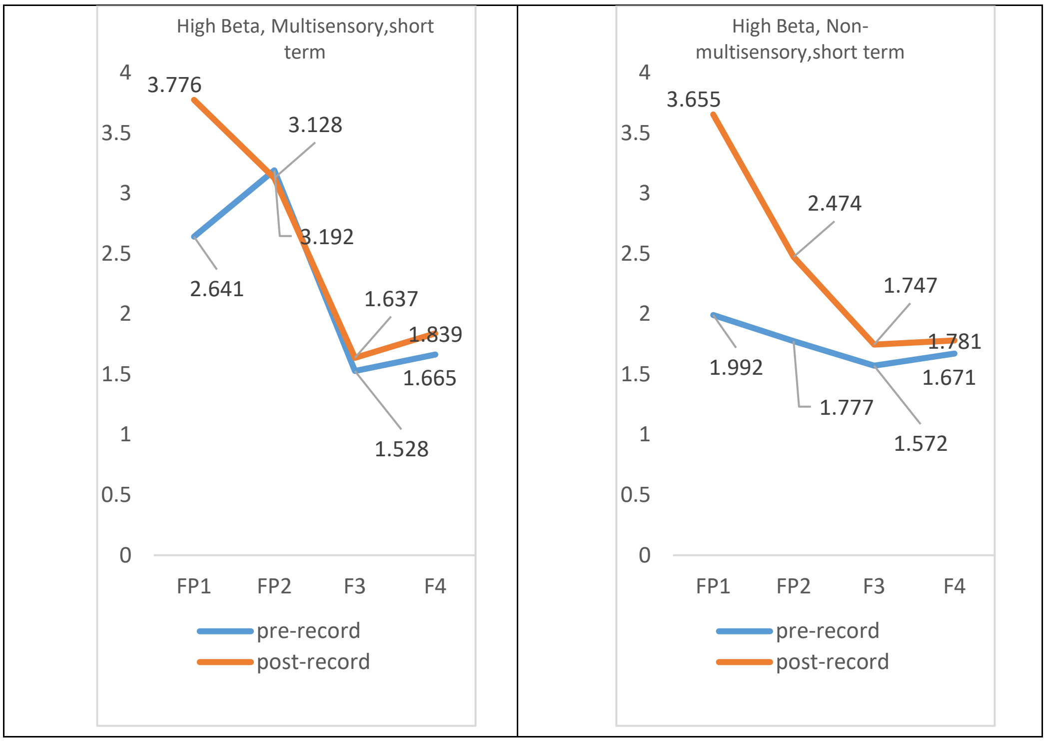

Figure 3. High beta frequency changes on Fp1, Fp2, F3, and F4 at QEEG pre- and post-records of the multisensory and non-multisensory groups at short-term retention

In a clinical study, Ogrim et al. (2012) examined the correlations of behavioral parameters and beta rhythm frequencies in sixty-two participants (thirty-nine normal subjects and twenty-three subjects with Attention-Deficit / Hyperactivity Disorder/ ADHD); correspondingly, they found no significant relationship between high beta frequencies and behavioral parameters.

The brain maps investigation demonstrated changes in brain activities before and after 30 minutes of instruction, which were not statistically significant (Figure 4).

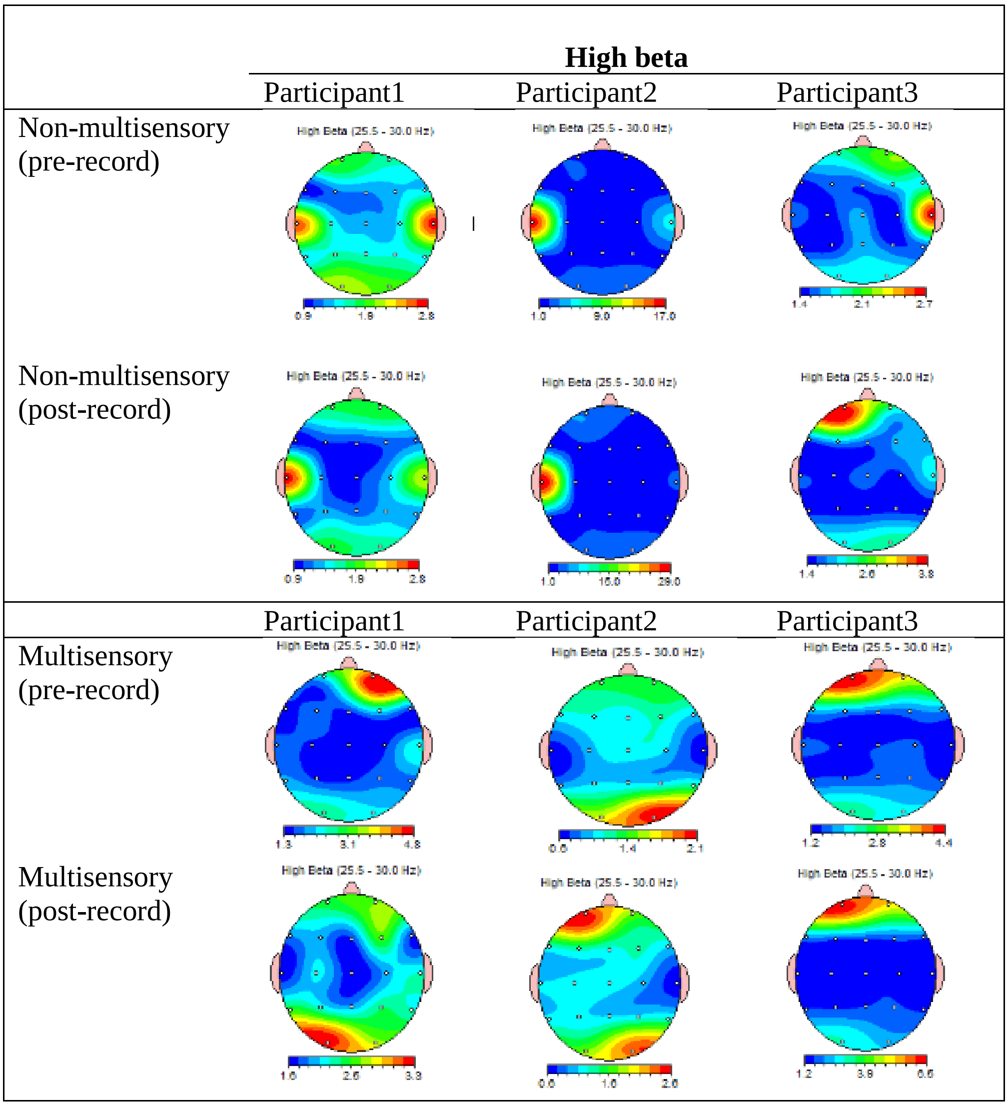

Figure 4. The post QEEG records after treatment (multisensory and non-multisensory teaching) (Green = Normal; Red = Excessive; Blue = Diminished Activity)

The non-parametric Mann-Whitney U test was used to compare the mean scores. The results indicated that there was no significant difference (p>0.05) between the mean scores of the post-tests in multisensory and non-multisensory groups (Table 3).

Table 3. Statistical indices of the Mann-Whitney U test, comparing post-test scores of multi-sensory and non-multisensory groups

Group	N	Mean Rank	Sum of Ranks	U	Sig
Multisensory	3	4.33	13.00	2.00	0.26
Non-multisensory	3	2.67	8.00		
Total	6				

The application of Kendall's Correlation Coefficient test on beta and beta1 (SMR) mean absolute power frequencies at Fp1, Fp2, F3, and F4 brain regions of the six participants of both multisensory and non-multisensory groups in short-term retention indicated that there was a significant positive correlation ($p<0.05$) between beta wave frequency changes at post-records on Fp1 and Fp2 regions and EWPMT mean score at post-test in multisensory group (Table 4). That is, the more the beta wave frequency increased at Fp1 and Fp2 regions of the brain, the more the scores on the EWPM post-test were in the multisensory group.

Table 4. Statistical indices of Kendall's Correlation Coefficient test to investigate the relationship between beta and beta 1 frequencies and EWPMT mean scores

Variable		Multisensory		Non-multisensory	
		r	Sig	r	Sig
Beta	FP1	1.00**	0.000	-0.81	0.22
	FP2	1.00**	0.000	-0.81	0.22
	F3	-0.33	0.60	-0.81	0.22
	F4	0.33	0.60	-0.81	0.22
Beta1	FP1	0.33	0.60	-0.81	0.22
	FP2	0.33	0.60	-0.81	0.22
	F3	0.33	0.60	0.00	1.00
	F4	0.33	0.60	-0.81	0.22

The statistical analyses (Kendall's Correlation Coefficient test) demonstrated that there were no significant relationships ($p>0.05$) between beta wave frequency changes on Fp1, Fp2, F3, and F4 at post-records and EWPM post-test mean score in the non-multisensory group.

The results of the Kendall's Correlation Coefficient test on high beta mean absolute power frequencies at Fp1, Fp2, F3, and F4 regions of the three participants of both multisensory and non-multisensory groups denoted that there was a significant negative correlation ($p<0.05$) between high beta wave frequency changes at post-records on F3 region and EWPMT mean score at post-test in multisensory group in short-term vocabulary retention phase (Table 5). To put it differently, the decrease in high beta frequencies on the F3 region of the brain is accompanied by higher scores on EWPMT.

Table 5. Statistical indices of Kendall's Correlation Coefficient test to investigate the relationship between high beta frequencies and EWPMT mean scores

Variable		Multisensory		Non-multisensory	
		r	Sig	r	Sig
Highbeta	FP1	0.33	0.60	-0.81	0.22
	FP2	0.33	0.60	-0.81	0.22
	F3	-1.00	0.000	-0.81	0.22
	F4	-0.33	0.60	-0.81	0.22

Low-Resolution Brain Electromagnetic Tomography (LORETA) Interpretation

LORETA was used to create contemporary source concentration images of brain wave activities. Localization of the brain waves density in EEG activity in the two groups was assessed voxel-by-voxel. In addition, the three-dimensional source distribution was computed for all the participants.

The LORETA analyses in the short-term multisensory group's post records and the first best matches showed that the Parahippocampal Gyrus on limbic lobe was significantly more active as compared to the non-multisensory group. In the three-dimensional tomography of the three participants in the multisensory group, Brodmann area 30 and Hippocampus were shown as the active areas correlated to the Parahippocampal Gyrus in the limbic lobe (Figure 5).

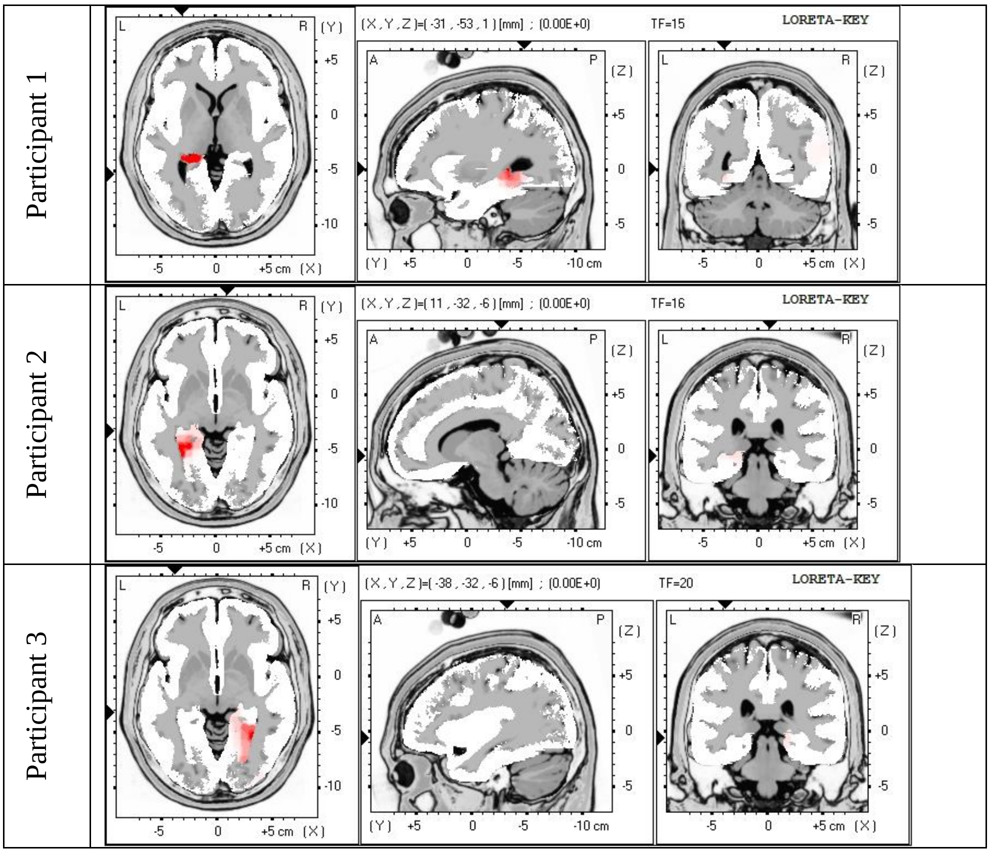

Figure 5. LORETA tomogram showing increased activity signals localized to the Parahippocampal gyrus

The LORETA results suggested that the signals are located in the cingulate cortex (area 30) and the hippocampus area for the first best match, which are located in the limbic lobe. The cingulate gyrus is a part of the limbic lobe, which is located around the corpus callosum and continues into the medial temporal lobe to join the parahippocampus (Brodmann & Garey, 1994).

These types of localization have not been found in the three participants of the non-multisensory group's post-records, and the acquired data on LORETA analysis indicated scattered localization on brain areas 41, 35, and 13.

During the emotionally arousing learning situation and memory storage, the parahippocampal gyrus and ventrolateral prefrontal cortex receive amygdala influences (Kilpatrick & Cahill, 2003). Amygdala is a part of the limbic system near the parahippocampal region during a heightened emotional arousal outflow, and its increased cascading reflects well-established memory modulating ability (Kilpatrick & Cahill, 2003). Research with animals proved that hippocampal/parahippocampal complex memory-related activities were affected by the amygdala (Guyton & Hall, 2006; Tyng et al., 2017). Consistent with these findings, the present study indicated higher activities in the parahippocampal complex, which is related to higher retention scores on the post-test in the multisensory group.

Besides, the limbic-temoral lobe is directly related to the olfactory network, and the sensory processing at the Limbic Lobe could be modulated by learning and memory (Martin & Ravel, 2014). The oscillatory activities of beta (15-40 Hz) and gamma (60-100 Hz) rhythms in the olfactory system have been reported to be modulated during olfactory processing (Fourcaud-Trocmé et al., 2019). The multisensory groups' olfactory activities (smelling some of the manipulatives) might have activated the olfactory system and consequently the Limbic lobe and might have modified beta rhythms activities in this area of the brain that itself enhanced memory and learning in this group.

5. Discussion and Conclusion

The present inquiry was conducted to apply QEEG data to FL teaching field. Since the brain is a multisensory organ and learning will happen as a result of stimulation through senses (Fernald, 1943; Gillingham & Stillman, 1997; Morgan, 2019), the study designed to empirically scrutinize these changes in the field of language teaching by using a noninvasive device (QEEG).

In the present study, the FL vocabulary short-term memory performance in two groups of multisensory and non-multisensory instructions using QEEG data were examined. Beta, beta1, and high beta waves frequency ranges were recorded on prefrontal and frontal regions (Fp1, Fp2, F3, and F4) and brain maps' topography were analyzed before and after instructions. Though the case analyses of the results reiterated the supremacy of multisensory teaching in FL vocabulary retention, the findings were not statistically significant. These surprising results might be due to the state of the study (after-instruction-record instead of during-instruction record) or to the small number of participants (only 3 participants in each group).

No significant correlation was signified between FL learners' mean score on the post tests and beta wave frequency increases on Fp1 and Fp2 areas in post records of the multisensory group.

The mean absolute powers of beta increased at post-records, but the data were not statistically significant. The increase in beta band frequency showed the positive effect of both instructions (multisensory and non-multisensory) on beta wave frequencies. Higher beta and beta1 wave frequencies are mentioned to be accompanied by higher concentration, energy, performance, and focused attention (Demos, 2005; Guyton & Hall, 2006) and consequently will result in learning improvement (Prat et al., 2016). Beta1 (SMR) wave frequencies were decreased in the non-multisensory but increased in the multisensory group, which indicated the supremacy of multisensory instruction regarding beta1 improvement in comparison to the non-multisensory group in this particular population. The EEG records on auditory memory tasks were analyzed by Pesonen et al. (2006), and the results indicated activation of beta rhythms as reflecting cognitive and memory processing. Pesonen et al.'s (2006) findings similarly reinforce the case-analyses results of the present study, which is the activation of the beta wave rhythms in both multisensory and non-multisensory groups.

Beta wave frequencies are ascribed to improvement in performance and learning (Marcuse et al., 2015), and the prefrontal regions (Fp1and Fp2) are associated with higher memory storage and recall (Guyton & Hall, 2006). Concentration and attention are ascribed to beta wave increases in prefrontal and frontal brain regions (Lim et al., 2019). Applying EEG to measure brain wave changes in thirty-two college students during a focus task, Lim et al. (2019) found that beta waves increased during concentration and immersion in the occipital and frontal lobes, with a higher increase in immersion. In line with Lim et al. (2019), the data on beta wave frequencies indicated higher activity on Fp1 and Fp2 regions.

Beta1 wave is a high-frequency and low-amplitude wave associated with introverted and focused concentration (Martin & Ravel, 2014). The introverted concentration would lead to the greater use of cognitive and metacognitive strategies in FL learning (Kayaoğlu, 2013). The prefrontal region plays an attested role in metacognition (Takeuchi et al., 2019); therefore, an increase in beta1 wave frequencies would be associated with improvement in learning and retention.

The frequency of high beta wave ranges between 22 and 30 Hz and is accompanied by hypervigilance and high-speed cognitive processing, anxiety, and bruxism (Marcuse et al., 2016). The prefrontal cortex is affected by anxiety, which itself would alert the cerebral lateralization of dopamine activity and, as a result, excitement (Fride & Weinstock, 1988). A different experiment by Puig et al. (2014) showed that blocking dopamine receptors in the prefrontal cortex impairs incoming stimulus-response learning and cognitive flexibility, while it does not cease the memory of highly familiar associations.

The increase in high beta frequencies was more pronounced in the non-multisensory group compared to the multisensory group. The findings provide some evidence for the potential effectiveness of multisensory instruction in anxiety management. Beta and beta1 brainwave activity supports learning improvements and should be strengthened, while excessively high-beta activity may require suppression during learning or task engagement (Tatum et al., 2008). This study focuses on the permanent or temporary effects of instruction on brain waves after the teaching period rather than during it. No significant differences in the results were observed.

The short-term memory is associated with areas in the prefrontal cortex, specifically the dorsolateral area, primarily on the left side, so around F3 (Herwig et al., 2003). High beta wave frequencies, accompanied by anxiety, increased in both experimental and control groups in post-records. However, their increase in the Multisensory group was desirable since it led to higher scores on post-tests. The one-by-one correspondence between the multisensory group's post-test scores and high beta frequency absolute power indicated this proportionality.

Decreasing high beta wave frequencies on the F3 region is desirable in learning (Marcuse et al., 2015) and consequently in retention (Ritter et al., 2013). The higher mean score on the EWPM-post-test in the multisensory group was associated negatively with lower anxiety in the prefrontal cortex. That is, higher anxiety caused by multisensory instruction might help learners improve their short-term memories and retain new FL vocabulary on the post-test.

Anxiety and excitement derive from similar neuro-chemical mechanisms in the brain, with their differentiation comes from the cognitive associations individuals attribute to these states. Imbalanced excitement, however, induces intensified dopamine release within behavior-regulating neural regions, particularly the frontal lobes (Guyton & Hall, 2006).

The humans' cognitive processes like perception, reasoning, learning, and even problem-solving are influenced by emotion (Tyng et al., 2017). Retrieval, encoding, and memory will be facilitated by attentional control (Tyng et al., 2017). Multisensory classes are full of emotion, they incorporate participation, excitement, games, and sensory manipulations which lead to retention.

The case study related to the scores on post-tests indicated improvement in language scores, but the results were not statistically significant. The sample is too small to draw a conclusion on this result and generalize the findings. The individual scores for each learner on the post-test indicated the effectiveness of both instructions (multisensory and non-multisensory).Even though the perceptual function is built upon a multisensory foundation (Molholm, et al., 2002; Noel et al., 2017) and multisensory instruction improve vocabulary learning (Gorjian et al., 2012), the findings of the study showed no significant improvement on post-test scores in the multisensory group in comparison to the non-multisensory group. The mean scores of the participants on the post-test in the multisensory group revealed that the learners in this group outperformed their counterparts in the non-multisensory group.

Moreover, the teacher's observations during the exam indicated that children in the multisensory group not only recalled the target vocabulary but also remembered related words within the same semantic network, allowing them to respond more quickly.

The qualitative results of the study are in line with Jubran's (2012) findings that asserted the effectiveness of multisensory instruction in teaching English skills. Applying experimental design, Jubran (2012) investigated the effect of multisensory teaching in comparison to traditional one in two groups of 122 participants, and the results indicated students' performance enhancement in the multisensory group.

Broadbent et al. (2018) employed multisensory educational tools and advocated the benefits of multisensory information over unisensory cues for learning. They examined the retention of incidental categorical learning in 5-, 7-, and 9-year-olds (N=181), comparing multisensory and unisensory cues. In line with Broadbent et al. (2018), Baker and Jordan (2015) reported the beneficial presentation of multisensory cues on the immediate acquisition of numerical abilities. The empirical results of these studies affirmed the qualitative findings of the present study, that is, the effectiveness of multisensory processing in the brain on the learner's performance.

The LORETA analyses illustrated the activity localization on the parahippocampal gyrus in the multisensory group's post-records. It shows that multisensory instruction is an advantageous approach to teaching new FL vocabulary items. Since almost all studies on brain oscillations have recorded brain waves during task performance or instruction, rather than after it (e.g., Ghetti & Alexander, 2004; Hsu et al., 2017; McEvoy et al., 2000), it is challenging to make direct comparisons between published studies and the present one.

Regarding external validity, valid results are often in agreement with other research. As reported, previous research showed positive significant relationships between beta, and beta1 bands elevation and learning and attention (Demos, 2005; Güntekin et al., 2013; Ritter et al., 2013; Wróbel, 2000); while, the related studies indicated the negative significant correlation between high beta wave frequencies and attention and learning (Chiu et al., 2006; Demos, 2005; Ghetti & Alexander, 2004). Contrary to other studies, the present study's findings were not in agreement with the previous ones in the field. This unexpected result is mainly due to the limited number of participants (only 6); therefore, the results lack external validity and generalizability.

Considering the results of the case analyses, the findings revealed valuable insights. This empirical experiment offered a comprehensive investigation into the applications of the QEEG device in language learning. Further, it contributed to the development of related discussions on brain waves and instructional programs. The findings have several implications.

First, they provide FL educators and researchers with a scientific basis to explore interdisciplinary approaches (e.g., multisensory approaches) to language teaching and learning. Second, they offer psychologists and neurologists opportunities to examine the neural areas involved in FL learning and how these may be affected by methodological variations. Moreover, the results may assist language teachers in becoming familiar with scientific techniques of methodological evaluation and in adopting more effective instructional practices.

Despite these advancements, certain limitations must be considered. The relatively small sample size restricts the generalizability of the results. Besides, this study was conducted over a limited time frame, which did not allow examination of the long-term effects of QEEG-based interventions. Finally, the focus was refined to specific tasks and contexts, while factors such as learners' age, proficiency levels, and affective variables were not fully addressed. These limitations suggest that the findings should be interpreted with caution and warrant further, large-scale investigations.

Future research is recommended to identify further the brain regions and oscillatory patterns engaged in FL/SL learning, to enhance language teaching, and to investigate potential long-term or transient changes in brain waves resulting from specific tasks or instructional periods.

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