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Brain-wide gamma activity during passive listening of rhythmic Quranic recitations in a naturalistic setting under MEG/EEG simultaneous recording

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Abstract: The involvement of high-frequency brainwaves in the neural processing of rhythmic Quranic recitation remains unclear, compared to the low-frequency brainwaves. This study examined the synchronisation of high-frequency gamma brainwaves (30–80 Hz) during passive listening to Quranic recitation in three different rhythmic styles. This experimental, cross-sectional study involving 29 healthy adult participants (14 Muslim, 15 non-Muslim) was conducted at the MEG laboratory at Universiti Sains Malaysia, Kubang Kerian, Kelantan, Malaysia. The average gamma source estimation was calculated using minimum-norm imaging, and the whole-brain functional connectivity of magnetoencephalography-electroencephalography (M/EEG) data was quantified using phase-locking value. The results revealed that the gamma waves synchronised in a network of brain regions that included the supramarginal gyrus, anterior cingulate cortex, hippocampus, central region, temporal lobe, inferior frontal gyrus, Rolandic and frontal operculum, cerebellum, visual network regions, and superior parietal gyrus. The findings highlight brain-wide activation during Quranic recitation in Quran-naïve non-Muslim participants, comparable to that in Muslim participants familiar with the employed rhythmic recitation. Both groups also exhibited increased language perception of the Quranic recitation, although they did not understand Arabic (non-Arab natives). The high-frequency gamma activity in this study suggests that receptive listening to different styles of rhythmic Quranic recitation engages neural networks responsible for language and musical perception, emotional regulation, memory and attention, visual mental imagery, and multisensory processing.

Keywords: Functional connectivity; Quranic recitation; Gamma brainwave; Magnetoencephalography (MEG); Electroencephalography (EEG).

1.0 INTRODUCTION

In Islam, the Quranic verses are a unique Arabic-language rhythmic text accompanied by a melody and cadence that arise from the combination of its words and letters, which are grounded in beautiful and sacred semantics. In its recitation routine, the application of tajweed, a set of disciplined and specific recitation rules, also contributed to the unique sound of the Quran, which separates it from other Arabic poetry and speeches. The incorporation of this tajweed rule conforms to the recitation of the Quran the way it was divinely revealed to Prophet Muhammad PBUH over 1400 years ago. Additionally, there are varying styles of recitation which rest on the different qiraat, where over 95% of the Muslim population adopted Qiraat 'Asim (Yasir Qadhi, 1999) and the other qiraat, such as Qiraat Susi, is mainly used in the African region.

The differences in qiraat lie in the application of the tajweed rules during recitation. These distinct recitation rules result in a variety of melodic sounds produced during the recitation of the Quran. The differences in sound can be small and subtle, noticeable only to those familiar with the Quranic verse and the tajweed and qiraat combination. The exegesis of the Quranic verse is the same in all of the recitations, and the meaning of the words is maintained while still adhering to the tajweed guidelines.

Furthermore, the rhythmic recitation of the Quran is perfected and embellished by the use of a melodic tarannum, which acts as the external musical feature of the Quran. The recitation is much slower in tempo, with varying intonations emphasised in certain verses. As such, these recitation rules and styles of reciting the Quran make it distinctively disciplined, melodious, and rhythmic with different tempos, befitting the spiritual purposes for Muslims worldwide.

A recent review revealed that listening to, reciting, or memorising the Quran may be beneficial for physical and mental health among Muslims (Che Wan Mohd Rozali et al., 2022). A recent comprehensive review showed that most studies on the Quran research highlighted the analysis of brain frequency's power using electroencephalography (EEG) (Kannan et al., 2022), exclusively on low-frequency brain waves such as theta and alpha oscillations. This is attributed to the notion that the presence of these low-frequency brain waves reflects the brain's relaxed, calm state.

According to such studies, listening to Quranic recitation increases the theta brainwave (Reza et al., 2012; Vaghefi et al., 2015) and alpha power (Al-Galal & Alshaikhli, 2017). Neuronal oscillations indicate the neural correlation between listening to Quranic recitation and various cognitive processes, such as attention (Mohd Nasir & Wan Mahmud, 2015), memory (Reza et al., 2012) and visual mental imagery (Ismail et al., 2022). In addition to the relaxation and calming effects of Quranic recitation on listeners, regardless of their understanding of the Quranic verses, listening to Quranic recitation also displays increased brain complexity and dynamics (Vaghefi et al., 2019). However, limited literature exists on Quran listening, focusing on high-frequency brainwaves such as gamma (Kannan et al., 2022).

In the hippocampus, gamma brainwaves are robustly present and play an essential role in memory functions (Buzsáki, 2015). It has been shown that gamma activity and spiking information are increased during a working memory task (Lundqvist et al., 2018). Since they can enhance time-dependent spike plasticity and promote inter-regional neuronal communication, gamma oscillations are conducive to long-term memory consolidation (Burke et al., 2015). In fact, gamma rhythm dysfunction has been shown to be associated with memory impairment, a hallmark of Alzheimer's disease (Traikapi & Konstantinou, 2021).

Furthermore, in expert meditators, an increased gamma brainwave activity in both brain hemispheres has been shown (Fell et al., 2010), as well as in the parieto-occipital region (Braboszcz et al., 2017). This increased gamma power may be correlated with sustained selective attention, which is the ability to focus on a task and avoid being distracted by intrusive thoughts. An increased self-awareness has also been proposed as a factor, as meditators are often more aware of their thoughts and feelings (Lee et al., 2018).

Previous studies have explored the effects of Quranic recitation on cognitive function in naturalistic settings. These studies have found that Quranic recitation improved a variety of mental functions, such as attention (Mohd Nasir & Wan Mahmud, 2015), memory (Reza et al., 2012), and learning (Hojjati et al., 2014). However, understanding how the brain processes information in naturalistic settings remains challenging, as most current knowledge regarding brain function comes from studies that use task paradigms (Simony & Chang, 2020). The human brain can process several information daily by synchronising neuronal oscillations. This synchronisation allows different parts of the brain to communicate with each other and share information effectively throughout the entire brain network.

In particular, listening to music in naturalistic settings has been shown to activate several brain regions. The default mode network, a network which is active during rest (Buckner et al., 2008), has been shown to increase connectivity when listening to different types of music (Wilkins et al., 2014). Moreover, listening to music can also activate the motor regions similarly when movement is initiated (Matthews et al., 2020). This study also found that the reward network is activated when listening to music. However, empirical research on the rhythmic Quranic recitation from this perspective remains scarce. Previous studies on the Quran, which mostly used EEG, focused on analysing variations in brainwave power. Therefore, the neural network or brain regions involved in processing the Quranic recitation remain unexplored. To address this, the source estimation of gamma brainwaves and the gamma phase synchronisation of the whole-brain functional connectivity using a simultaneous recording of magnetoencephalography (MEG) and EEG were examined, the first approach of its kind for a Quranic recitation study.

2.0 MATERIALS AND METHODS

2.1 Participants

This experimental, cross-sectional study involving 29 healthy adult participants (14 Muslim and 15 non-Muslim) was conducted at the MEG laboratory at Universiti Sains Malaysia, Kubang Kerian, Kelantan, Malaysia, from July 2014 to May 2016. The participants were non-native Arabic speakers, aged between 21 and 35 years old, with no formal musical training and reported no significant hearing loss or history of neurological diseases, mental disorders, movement disorders, or substance abuse disorders. Participants were excluded from the study if they had exogenous or endogenous metal implants, head sizes that were too large or small for the MEG machine, or a State-Trait Anxiety Inventory score of 50 or higher. The study protocol was approved by the USM Human Ethics Committee (FWA Reg No: 00007718; IRB Reg No: 00004494). All participants provided informed written consent.

2.2 Rhythmic Quranic recitation stimuli

The M/EEG signal was recorded while participants passively listened to three styles of Quranic recitation of the Ayatul Kursi verse. The three styles were Murattal Asim, Murattal Susi, and Tarannum Asli. Murattal Asim and Susi have moderate tempos, while Tarannum Asli has the slowest tempo (tahqiq). Murattal ‘Asim and Susi are different in qiraat, that is, Qiraat ‘Asim and Qiraat Susi, respectively, in which the pronunciation of certain words has subtle differences. Meanwhile, Murattal ‘Asim and Tarannum Asli are in the same qiraat (Qiraat ‘Asim) but with different tempos in the recitation. The Ayatul Kursi verse was recited by the same reciter, Sheikh Hisyam Al-Bari, an Egyptian Qari who is well-versed in Arabic texts and different Quranic recitation styles. The participants were unfamiliar with Sheikh Hisyam Al-Bari’s voice. Ayatul Kursi was selected for this study because it is a highly significant verse among Muslims and is considered the “throne verse,” reflecting divine attributes that bear psychospiritual healing values.

2.3 M/EEG recording

To reduce external interference that could disrupt data collection and minimise volunteer fatigue, the M/EEG recording sessions were performed in the morning (usually between 8:30 AM and 11:30 AM). Before participants entered the magnetically shielded room (MSR) to record their brain responses, the MSR was measured without participants present. This was performed to verify that the noise covariance estimation was stable and reproducible. A total of 3 min of empty-room recordings was obtained.

MEG and EEG were recorded simultaneously in the MEG laboratory at Universiti Sains Malaysia using a Vectorview TMS 306-channel MEG system (Elekta Neuromag, Finland) combined with a compatible 64-channel EEG system (ANT Neuro WaveGuard EEG cap, Germany) using the International 5-10 System. The MEG system consists of 204 gradiometers and 102 magnetometers. Before entering the MSR, participants were asked to remove any metal, electronics, or clothing containing metal.

The EEG impedance was continuously measured to ensure that it was below 5 kOhms. The four HPI coils and anatomical landmarks, including the three bony fiducial points (nasion, LPA, and RPA), were digitised using a stylus. Additionally, approximately 200 more digitisation points were included to gain more information regarding the head shape. This process was vital because the quality of the source analysis to be performed depended heavily on accurate registration between the channel sensors and the anatomy.

All participants were placed in the MSR and wore MEG-compatible earphones to deliver auditory stimuli. They were seated at a 45-degree angle. The low- and high-pass filters were set to 330 Hz and 0.1 Hz, respectively, with a sampling rate of 1000 Hz. The receptive listening data were collected while the participants were awake, alert, and with their eyes closed. The auditory stimuli were randomly presented for receptive listening, with 3 min per stimulus and a 1-minute gap before the next stimulus. The recitations were played at a moderate 60–65 dB, matching typical conversation levels, and the pitch was kept natural to preserve authenticity.

2.4 M/EEG data processing and analysis

Using the temporal extension of signal-space separation (tSSS), the external interference source from the MEG raw data was removed (Taulu & Simola, 2006) as implemented using the MaxFilter V2.2 software (ElektaNeuromag, Finland). The tSSS corrected the head position and the associated movement-related artefacts by identifying their correlated temporal behaviour inside and outside the sensor helmet. Brainstorm, an open-source software, was used to pre-process the recorded M/EEG raw data (http://neuroimage.usc.edu/brainstorm).

The data were transformed from the time domain to the spectral domain using Welch power spectral extraction. The 50-Hz power line noise and its harmonics were removed using a notch filter. Bad channels were identified and excluded from further analysis because they provided no useful information regarding brain activity. A band-pass filter was used to eliminate insignificant frequency ranges outside the common bands delta, theta, alpha, beta, and gamma (1–80 Hz). Interference in the MEG and EEG brain signals by common physiological sources such as cardiac muscles, skeletal muscles, and saccades, was removed using signal-space projection (SSP). Finally, to remove any residual artefacts that could not be correctly reduced by SSP, an independent component analysis was performed.

The default anatomy (ICBM152) was imported into Brainstorm and used for anatomical registration to compute the head model. Brainstorm's warping algorithm was used to affinely transform the ICBM152 anatomical template. The warping process scales and deforms the magnetic resonance imaging (MRI) template and surfaces to match the shape defined by the digitised head points. Then, the volume source estimates of gamma brainwaves from all participants were averaged within groups and calculated using minimum norm imaging (MNI). The Automated Anatomical Labelling Atlas 3 (AAL3) brain atlas, which has 170 brain regions, was selected. To examine the correlation between the average estimated gamma source, a nonparametric Spearman correlation was performed. Statistical significance was set at $p < 0.05$. The M/EEG data were also analysed using phase locking value (PLV) to measure functional connectivity between brain regions.

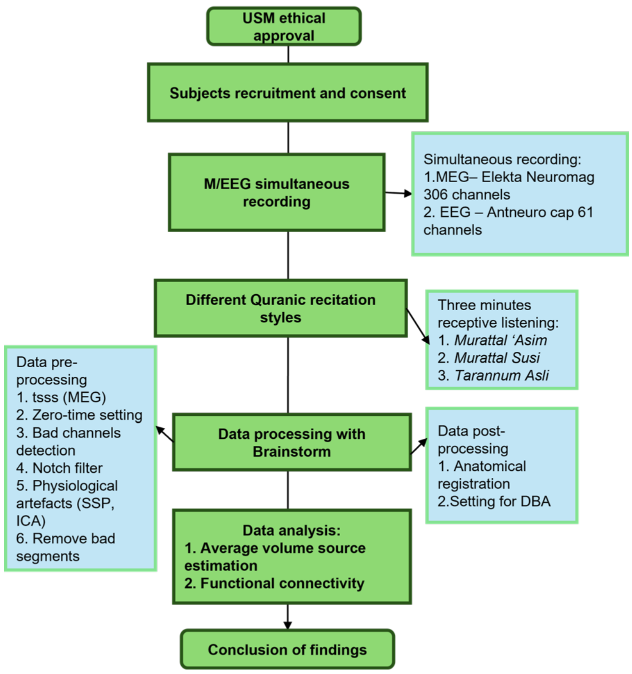

Figure 1. Summary of the methodology

A full network connectivity (N x N) was computed, as the analysis would thoroughly calculate the functional graph, albeit at the expense of more extensive computation. A non-parametric permutation test was performed to analyse the functional connectivity between the brain regions in the gamma brainwave (Nichols & Holmes, 2002). The permutation distribution of the statistic of interest was approximated using the Monte Carlo approach, with 1000 random permutations. A false discovery rate correction was used to correct for multiple comparisons. A statistically significant difference was set at $p < 0.05$. The significant functional connectivity was presented through the connectivity graph. **Figure 1** shows a summary of the methodology.

3.0 RESULTS

3.1 Average source estimation

The average gamma source estimation was obtained by averaging the gamma signals using an MNI, which estimates the amplitude of brain sources distributed across the brain. The MEG and EEG data for the three recitation styles for both groups are presented in **Figure 2**. A summary of the findings is presented in **Table 1**. The correlations among brain regions were then determined, as shown in **Table 2**, **Table 3**, and **Table 4**, for the respective MEG and EEG modalities.

Table 2 shows a statistically significant correlation (moderate to high) between most of the brain regions involved in both Muslim and non-Muslim groups for Murattal ‘Asim in the MEG and EEG datasets.

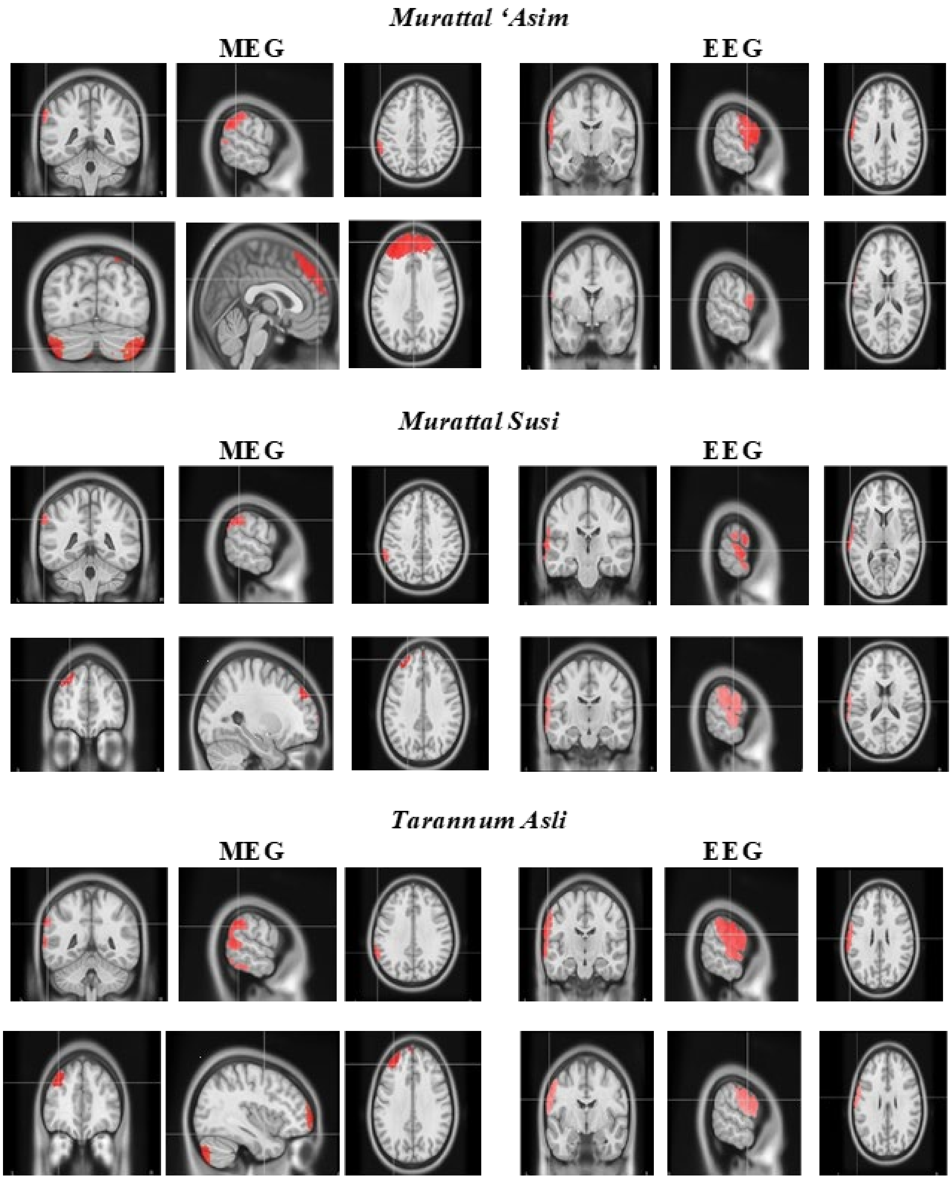

Figure 2. Average volume source estimation of the gamma activity in the *Murattal ‘Asim, Murattal Susi*, and *Tarannum Asli* style for both groups. Figure note. Upper panel: Muslim group. Lower panel: Non-Muslim group.

Table 1. Summary of average gamma source estimation.

Recitation style	Group	Modality	
		MEG	EEG
Murattal 'Asim	Muslim	Left supramarginal gyrus, left temporal region	Left Rolandic operculum, left precentral region
	Non-Muslim	Bilateral frontal, bilateral cerebellum	Left postcentral region, left inferior frontal operculum
Murattal Susi	Muslim	Left supramarginal gyrus, left parietal region	Left temporal region, left postcentral region
	Non-Muslim	Left frontal region	Left temporal region, left postcentral region
Tarannum Asli	Muslim	Left temporal, left parietal, bilateral cerebellum regions	Left inferior frontal gyrus (IFG), left postcentral region
	Non-Muslim	bilateral frontal, bilateral cerebellum regions	Left inferior frontal gyrus (IFG), left precentral region

Table 2. The correlation of average gamma source estimation between brain regions for *Murattal 'Asim*.

MEG							
	Brain regions						
Muslim	**r**	**Left SM**	**Left temporal**	**Left frontal**	**Right frontal**	**Left Cb**	**Right Cb**
	Left SM		0.921**	0.969**	0.934**	0.657**	0.622*
	Left temporal	0.921**		0.916**	0.846**	0.767**	0.710**
	Left frontal	0.969**	0.916**		0.912**	0.640*	0.596*
	Right frontal	0.934**	0.846**	0.912**		0.556*	0.530
	Left Cb	0.657*	0.767**	0.640*	0.556*		0.938**
	Right Cb	0.622*	0.710**	0.596*	0.530	0.938**	
Non-Muslim	**r**	**Left SM**	**Left temporal**	**Left frontal**	**Right frontal**	**Left Cb**	**Right Cb**
	Left SM		0.836**	0.793**	0.771**	0.218	0.221
	Left temporal	0.836**		0.768**	0.818**	0.314	0.221
	Left frontal	0.793**	0.768**		0.779**	0.400	0.425
	Right frontal	0.771**	0.818**	0.779**		0.418	0.357
	Left Cb	0.218	0.314	0.400	0.418		0.886**
	Right Cb	0.221	0.221	0.425	0.357	0.886**	

EEG					
	Brain regions				
Muslim	**r**	**Left Rol_Oper**	**Left precentral**	**Left postcentral**	**Left IFO**
	Left Rol_Oper		0.912**	0.947**	0.855**
	Left precentral	0.912**		0.947**	0.881**
	Left postcentral	0.947**	0.947**		0.842**
	Left IFO	0.855**	0.881**	0.842**	
Non-Muslim	**r**	**Left Rol_Oper**	**Left precentral**	**Left postcentral**	**Left IFO**
	Left Rol_Oper		0.743**	0.857**	0.829**
	Left precentral	0.743**		0.929**	0.768**
	Left postcentral	0.857**	0.929**		0.768**
	Left IFO	0.829**	0.768**	0.768**	

*Correlation is significant at p<0.05; **Correlation is significant at p<0.01; SM, supramarginal gyrus; Cb, cerebellum; Rol_Oper, Rolandic operculum; IFO, inferior frontal operculum.

Table 3 shows a highly statistically significant correlation across all brain regions involved in both the Muslim and non-Muslim groups in the MEG and EEG data.

From the MEG dataset, **Table 4** shows a statistically significant correlation across most brain regions in both the Muslim and non-Muslim groups for Tarannum Asli. From the EEG dataset, **Table 4** shows that in the Muslim group, there is a significantly high correlation among all brain regions, with a similar tendency observed in the non-Muslim group.

Table 3. The correlation of average gamma source estimation between brain regions for *Murattal Susi*.

MEG				
		Brain regions		
Muslim	**r**	**Left supramarginal**	**Left parietal**	**Left frontal**
	Left supramarginal		.808**	.835**
	Left parietal	.808**		.753**
	Left frontal	.835**	.753**	
Non-Muslim	**r**	**Left supramarginal**	**Left parietal**	**Left frontal**
	Left supramarginal		.954**	.814**
	Left parietal	.954**		.807**
	Left frontal	.814**	.807**	

EEG			
		Brain regions	
Muslim	**r**	**Left temporal**	**Left postcentral**
	Left temporal		.855**
	Left postcentral	.885**	
Non-Muslim	**r**	**Left temporal**	**Left postcentral**
	Left temporal		.925**
	Left postcentral	.925**	

**Correlation is significant at *p*<0.01.

Table 4. The correlation of average gamma source estimation between brain regions for *Tarannum Asli*.

MEG							
		Brain regions					
Muslim	**r**	**Left temporal**	**Left parietal**	**Left Cb**	**Right Cb**	**Left frontal**	**Right frontal**
	Left temporal		.727**	.824**	.767**	.719**	.908**
	Left parietal	.727**		.732**	.692**	.732**	.745**
	Left Cb	.824**	.732**		.903**	.477	.745**
	Right Cb	.767**	.692**	.903**		.552*	.780**
	Left frontal	.719**	.732**	.477	.552*		.785**
	Right frontal	.908**	.745**	.745**	.780**	.785**	
Non-Muslim	**r**	**Left temporal**	**Left parietal**	**Left Cb**	**Right Cb**	**Left frontal**	**Right frontal**
	Left temporal		.868**	.496	.511	.700**	.668**
	Left parietal	.868**		.161	.357	.579*	.579*
	Left cerebellum	.496	.161		.879**	.579*	.561*

EEG				
		Brain regions		
Muslim	**r**	**Left IFG**	**Left postcentral**	**Left precentral**
	Left IFG		.921**	.952**
	Left postcentral	.921**		.956**
	Left precentral	.952**	.956**	
Non-Muslim	**r**	**Left IFG**	**Left postcentral**	**Left precentral**
	Left IFG		.793**	.896**
	Left postcentral	.793**		.829**
	Left precentral	.896**	.829**	

**Correlation is significant at *p*<0.01; Cb, cerebellum; IFG, inferior frontal gyrus.

3.2 Functional connectivity, PLV

Using the AAL3 atlas, the functional connectivity of MEG and EEG signals was analysed in a reconstructed source space comprising 170 cortical sources. A reconstructed source space is more reliable to analyse than sensor data because the two modalities have different numbers of channels (306 channels for MEG and 61 channels for EEG). Hence, for MEG and EEG studies, understanding the estimated connectivity between brain areas is typically much more manageable at the source level than at the sensor level. Additionally, estimated connectivity interpretation can be linked to studies from other fields of neuroscience, such as anatomical connectivity studies, invasive electrophysiology, or fMRI connectivity analysis. This renders the interpretation more reliable (Gross et al., 2013). A full PLV network connectivity (N x N) was incorporated to more thoroughly calculate the connectivity graph. The significant PLV between the groups is presented as the connectivity graph (p<0.005) (as shown in **Figure 3**).

4.0 DISCUSSION

4.1 Average gamma source estimation

The increased average gamma activity of the MEG data in the Muslim group during receptive listening to Murattal 'Asim and Murattal Susi recitation at the left supramarginal gyrus could be attributed to the low language comprehension level. This is because actual words produce increased left-hemispheric gamma power during lexical activation than pseudowords (Bakker et al., 2015). This may be related to the Ayatul Kursi verse, which Muslim believers most frequently and extensively memorise. Certain Arabic words in the verse, such as Al-Qayyum and Al-'Azim in the first verse, are regularly used in zikr (remembrance of Allah). The familiarity of these words might entrain the gamma oscillations in these language-related brain regions. Due to the limited understanding of the language and the inability to understand Arabic by the listeners, we concluded that language cognition was present in the listeners, but perhaps only at a low level as a group average. Conversely, non-Muslims mostly demonstrated an increased gamma distribution at the frontal and cerebellar regions for the M/EEG data during listening to Murattal 'Asim and Murattal Susi recitation styles. The increased gamma activation in these regions might encompass speech and language perception (Mariën et al., 2014). The gamma distribution contributed to information projections from the frontal regions to the cerebellum, as evidenced by the participation of gamma in both the frontal and cerebellar regions as the estimated brain source. Furthermore, the cerebellum entrained the emotional speech perception (Adamaszek et al., 2017) and enhanced emotional episodic memory encoding (Fastenrath et al., 2022) as reported in previous studies. Based on this evidence, we postulate that listeners also perceive some emotional aspects during listening to Quranic recitations.

Additionally, the EEG data show an increase in gamma-wave distribution in the left Rolandic operculum (Muslim) and left inferior frontal operculum (non-Muslim), with both groups demonstrating increased gamma in the central regions. It has been shown that processing basic auditory stimuli involves postcentral areas and the supramarginal gyrus (Popescu et al., 2004) The central regions are included in the sensorimotor cortex, which has been implicated in musical mode processing (Lin et al., 2014) This suggests that the brain may have perceived the cadence and rhyme pattern of the Quranic recitation of Ayatul Kursi as musical. Additionally, the Ayatul Kursi recitation, which includes stressing and intonating each syllable according to the tajweed, entrains the sensorimotor cortex in processing the phonological information (Schomers & Pulvermüller, 2016) In addition, the contributions of somatosensory areas might be related to motor-auditory system interactions for efficient speech perception and comprehension (Zioga et al., 2023) This suggests that the recitation may have engaged the brain in a manner similar to music and speech perception. The gamma brainwave distribution at the frontal and Rolandic operculum may be connected to the central regulation of the motions of the oral and larynx during articulation (Triarhou, 2021). Interestingly, vocal sound imitation or covert singing has been shown to result in increased frontal operculum activation, with increased activation observed for tasks that involve the processing of rhythm and pitch (Mălîia et al., 2018).

Based on these findings, we opine that the participants, irrespective of the faith groups, may have recognised the presence of language and processed the language corresponding to what we found in gamma. Moreover, this activation pattern may be attributed to lower levels of language processing during receptive listening to the Quranic recitation, given that all participants are non-Arabic-language speakers. This is because language processing takes place in the left frontal operculum, also known as the pars opercularis of Broca's region (Mălîia et al., 2018). Future research on listeners who can understand Arabic could further affirm these postulates.

In both groups, bilateral cerebellar activation was observed in the MEG data during receptive listening to Tarannum Asli style. The presence of gamma brainwaves in the cerebellum provides strong evidence that it is involved in phonological processing (Bakker et al., 2015), due to the cerebellum is involved in encoding phonological information of verbal utterances (Mariën et al., 2014). The increased distribution of activation to the parietal, temporal, and frontal regions suggests that information is projected from the cerebrum to the cerebellum. The strong linkage between the cerebellum and cerebrum via the frontal lobe language regions further supports their anatomical and functional relationship (Jobson et al., 2022).

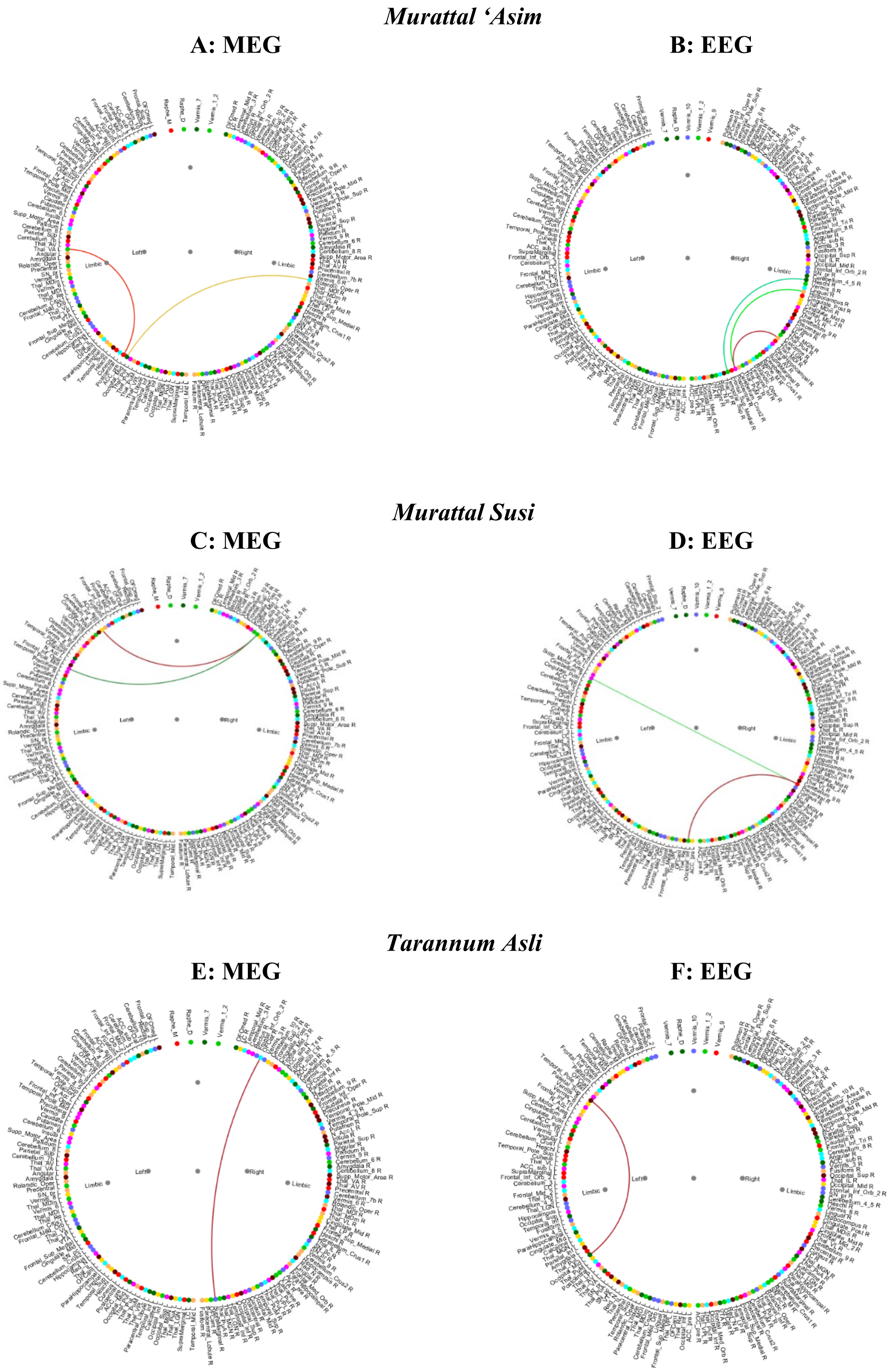

Figure 3. Significant functional connectivity of the gamma phase synchrony in the *Murattal 'Asim, Murattal Susi*, and *Tarannum Asli* recitation styles. **(A)** The significant functional connectivity is between the right Rolandic operculum and left middle occipital gyrus (MOG) and the left anterior cingulate cortex (ACC) and left thalamus ventral anterior (Thal_VA). **(B)** The significant functional connectivity between the right thalamus lateral geniculate nucleus (Thal_LGN) and right postcentral, right hippocampus and right postcentral, and right Heschl's gyrus (HG) and right superior temporal gyrus (STG). **(C)** The significant functional connectivity between the right IFG, the left IFG, and the left middle temporal gyrus (MTG). **(D)** The significant functional connectivity between the right precentral to the left IOG and the left cerebellum. **(E)** The significant functional connectivity between the right supramarginal gyrus and left lateral orbital gyrus (LOG). **(F)** The significant functional connectivity between the left middle occipital gyrus (MOG) and left superior parietal gyrus (SPG).

Meanwhile, EEG data showed increased gamma brainwaves in both groups in the left inferior frontal gyrus (IFG) and central regions. A previous study reported that gamma power in the IFG increased during semantic processing (Bakker et al., 2015). However, since the listeners in this study did not understand Arabic (non-Arab natives), semantic processing here is speculative. A lower level of language processing is possible, such as recognising common words from the recitation and associating them with meaning.

4.2 Functional connectivity (PLV)

The increased gamma phase synchrony between the right Rolandic operculum and left middle occipital gyrus (MOG) in the MEG data suggests that emotional regulation and self-awareness signals are integrated during receptive listening to Murattal ‘Asim recitation style. This is because the right Rolandic operculum is involved in processing emotion, as shown by a previous study that found an increase in psychological symptoms in post-stroke patients with a right Rolandic operculum lesion, including high levels of apathy, sadness, and anxiety (Sutoko et al., 2020). During actual Islamic prayer (salat), previous research has shown that gamma power increases when compared with mimic salat practice (physical motions without audible recitation) (Doufesh et al., 2016). The researchers postulated that the increased gamma power during salat practice was probably related to increased cognitive and attentional processing. In line with this, we could also associate with the norm of using Murattal ‘Asim in self-recitation of Quranic verses during salat, as it is widely used among Muslims to aid focus during salat.

Furthermore, the MEG data revealed functional connectivity between the left thalamus ventral anterior nucleus (Thal_VA) and the left anterior cingulate cortex (ACC). The increased gamma phase synchrony between the left Thal_VA and left ACC was a result of information relayed from the thalamus to the ACC. The thalamus, as a relay station, processes the physical properties of the Quranic recitation, such as rhythm and language, thereby initiating movement, such as covertly mimicking the recitation, and then transmitting the information to the ACC to perceive the emotional properties of the recitation. The increased gamma synchronisation in the left ACC could be correlated with the listeners' perception of the Quranic recitation as a positive experience, which in turn increased positive emotion. This interpretation stemmed from the role of ACC in processing positively valenced stimuli (Palomero-Gallagher et al., 2019).

Moreover, the increased gamma phase synchrony between the right hippocampus and the right postcentral gyrus could be attributed to musical mode processing (Lin et al., 2014) and speech perception (Schomers & Pulvermüller, 2016; Zioga et al., 2023). The phonological information from the Ayatul Kursi verse engaged the right postcentral gyrus, which assisted short-term recognition of the verse and entrained the hippocampus. This short-term recognition of the phonological information in the Quranic recitation is entrained in the hippocampus, a region essential for long-term memory and emotion regulation. The upregulation of the hippocampus was noted in the recall of positive autobiographical memories (Zhu et al., 2019).

During receptive listening to Murattal Susi's recitation style (of moderate tempo), MEG data showed functional connectivity between the right and left IFG, and between the right IFG and the left middle temporal gyrus (MTG). As Quranic recitation is a naturalistic stimulus with a distinctive rhythmicity and language presence, its processing requires greater stimulus evaluation that could result in right IFG activation (Hartwigsen et al., 2018). It is plausible that some listeners' unfamiliarity with Murattal Susi (even among the Muslim group) may reflect greater stimulus evaluation due to phonetic differences, though this remains speculative.

Pertaining to the EEG data, an increased gamma phase synchrony between the right precentral and left inferior occipital gyrus could be due to the perception of the place of articulation of the perceived phonemes and the mental imagery of the place of articulations and words (Schomers & Pulvermüller, 2016). Additionally, the EEG data also demonstrated functional connectivity between the right precentral and left cerebellar regions. As the right precentral regions are involved in the phonological processing of speech, the entrainment of speech phonological information is also encoded in the cerebellum (Mariën et al., 2014; Schomers & Pulvermüller, 2016). Hence, during phonological processing, gamma waves aided the projection of information between these regions. The synchronisation of gamma activity in these brain regions may converge on the language perception underlying the recitation of the Ayatul Kursi verse. These brain regions work together to process the phonological information in speech, enabling the perception of the place of articulation of phonemes and the mental imagery of the place of articulation and words.

Interestingly, MEG data demonstrated increased gamma phase synchrony between the right supramarginal gyrus and left lateral orbital gyrus (LOG) during receptive listening to Tarannum Asli style (slow tempo). A previous study has linked the LOG to the semantic processing of spoken language (Levitin & Menon, 2003). The functional connectivity of the LOG to the supramarginal gyrus is also consistent with previous research that has found that the LOG has strong connections to brain regions critical for higher-order cognition, such as the inferior parietal lobule and dorsolateral prefrontal cortex (Nestor et al., 2013). The supramarginal gyrus and angular gyrus form the inferior parietal lobule, which contributes to sensorimotor integration, spatial attention, and visuomotor and auditory processing. Based on this evidence, we argue that the functional connectivity between the right supramarginal gyrus and left LOG is related to the language processing of Quranic recitation, which entrains the synchronization of gamma oscillations.

Corroboratively, the increased gamma-phase synchrony between the left MOG and left superior parietal gyrus (SPG) in the EEG data may point to the multisensory processing role of the SPG. The functional connection of SPG to the visual network may relate to the processing of the auditory stimulus and the mental imagery of the stimulus, which emerges from the occipital region. Hence, it could be inferred that gamma oscillation synchronisation was involved in multisensory processing. This finding concurs with a study that found gamma oscillations in the superior parietal cortex assisted in the superadditive effect on task performance (Wiesman & Wilson, 2019). The entrainment of the left hemisphere might indicate the increased cognitive load in managing increased interference (Wiesman & Wilson, 2019). We speculate that the listeners augmented their attention to listen to the Tarannum Asli style recitation attentively; however, an increased interference in terms of spontaneous thought and mental imagery was observed.

A phenomenon in which the combined effect of two or more stimuli is greater than the sum of their individual effects is referred to as the superadditive effect (Stanford & Stein, 2007). This effect has been observed in language learning, where learners exposed to both auditory and visual input tend to learn more quickly than those exposed to only one modality. Studies on brain area interactions have demonstrated that even in mono-modal input, such as listening to a lecture, a linked activation exists in visual areas for auditory input and auditory areas for visual information (Cheetham, 2019; Stanford & Stein, 2007). This suggests that the brain is constantly integrating information from different sensory modalities, even when we are only consciously aware of one type of input. Therefore, brain areas that did not receive a direct input activate in tandem with those that did receive direct information (Cheetham, 2019; Stanford & Stein, 2007). Hence, the superadditive effect on the listening task has been influenced by the increasing gamma synchrony.

As a whole, the enhanced gamma phase synchrony between the middle occipital gyrus (MOG) and superior parietal gyrus (SPG) assisted multimodal processing and increased cognitive load in managing interference. This increased cognitive load may contribute to improved learning, as it forces us to pay more attention to the data input. Hence, the increased gamma synchrony between the MOG and SPG is likely a reflection of this multimodal integration and the increased cognitive load required to listen to Quranic recitation. These two brain regions are involved in visual and auditory processing, respectively, and their increased synchronisation suggests that they are working together to process the Quranic recitation's varying rhythmicity in a naturalistic setting, as employed in this study.

4.3 Limitations and future recommendations

Some of the limitations of this study include that the exact phonetic differences between the different qiraat of the Ayatul Kursi verse used in this study were not explored. Therefore, whether such phonological differences contribute to the neural presentation and functional connectivity differences observed remains unclear. Another limitation is the lack of quantification of the rhythmic features of the Quranic recitation. Quantifying rhythm, such as tempo, intonation patterns, and syllabic timing, could provide a more objective basis for examining how specific auditory features influence neural responses. Without such quantification, it is difficult to determine which aspects of the recitation may be driving the observed neural presentation. Future studies that evaluate the phonetic differences between the qiraat and the quantification of rhythmic Quranic recitation could serve as a valuable starting point for understanding these relationships. With this knowledge, it may be possible to decode the differences in phonetics and rhythmic features that contribute to neural presentation. A recent neuroimaging study has shown that the language a person is hearing or even just thinking can be decoded from fMRI responses (Tang et al., 2023).

5.0 CONCLUSIONS

Using simultaneous M/EEG recording for Quranic recitation research, this study shows the dynamics of high-frequency gamma oscillations during the processing of the naturalistic, rich rhythmicity of auditory stimuli such as Quranic recitation. Different brain regions and networks are engaged in different recitation styles (of slow to moderate tempo), aptly fitting with the routine practices and disciplines of Quranic recitation as taught by Prophet Muhammad PBUH over 1400 years ago. Brain regions involved in language and musical perception, emotional regulation, attention and memory, visual mental imagery, and multisensory processing seemed to be engaged during passive listening, in this case, to the recitations of an infamous Ayatul Kursi verse from the Quran. This suggests that the dynamics of Quranic recitation can be further investigated, particularly among those who understand Arabic. Of equal importance, the study also found brain-wide activation effects of Quranic recitation in non-Muslim participants, suggesting that the potential well-being benefit linked to Quranic recitation is not confined to Muslims, who are likely to be more familiar with the rhythmic Quranic recitation. In summary, the study findings suggest that listening to Quranic recitation impairs a variety of cognitive functions, including language processing, emotional regulation, attention, memory, and visual imagery, thereby enhancing overall well-being. This provided a solid foundation for applying Quranic recitation as a complementary sound and psycho-spiritual therapy, extending beyond its cultural and religious specificity. Further research on the role of gamma brainwave oscillations is warranted in a broader context, preferably using a dual synchronised M/EEG modality.

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