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Comparative study of event-related potential responses within syllables of intra and inter phoneme classes

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ABSTRACT

The present study was carried out to assess the signature neural dynamics as evinced through event-related potential (ERP) responses of the P300 waveform across different inter and intra phoneme consonant classes and to quantify the differential neural dynamical response in real-time. The ERP responses to non-sense three-syllable consonant-vowel transitions CVCVCV non-words were recorded on 26 healthy individuals of either sex with an age group of 18–25 years. The first syllable of the non-sense word was always fixed, and the ERP responses of the middle syllable were recorded at the phoneme level, and the ERP responses elicited by the middle syllable were evaluated. The results of the present study documented that different consonant phoneme classes (plosives, fricatives, affricatives, liquids, and nasals) elicited differential neural dynamical responses as observed through the P300 waveform response, exhibiting a significant difference in P300 waveform amplitude across the fricatives vs. nasals experimental design.

Keywords: event-related potential; phoneme; syllable; language processing; auditory events

1. INTRODUCTION

The present study has been conceptualised to understand the neural dynamical pattern dedicated to language. Spoken language, with its constituent foundation elements of phonemes and syllables, is a means of communication observable in humans across the globe, defined and profiled by respective letters and categorical phonemes and syllables, a precept described and explored through the science and art of phonetics (Kreidler, 1997).

A phoneme is a unit of sound that differentiates one word from another in a particular language. A phoneme is viewed as an abstraction of a set of speech sounds (phones) that are perceived as corresponding to each other in a given language. There are 44 phonemes in English, of which 24 are consonant phonemes and 20 are vowel phonemes (Wells & Wells, 1982). The vowels and consonants incidentally happen to be the primordial plasma for the evolution of a structured, sustainable, means of communication in the form of language, with the primary inclusion of a specific, dedicated admix of vowels and consonants producing recognisable and legible meaningful words that induce a combinatorial pattern of impulse generation within the recruited neuronal pools, specific and sensitive for that precise and distinctive meaningful word (Hochmann et al., 2011).

It has been further observed that the neuromuscular mechanisms involved in vocalisation of vowels are relatively simple as compared to those recruited for vocalisation of consonants, an observation that is exemplified by the fact that a newborn learns to ape and vocalise vowels first in phylogenetic development, followed by the evolution of consonants that appear late in life as a result of evolving neuromuscular maturational neural dynamics (Cheour et al., 1998).

A syllable is a unit of organization of an arrangement of speech sounds (De Jong, 2004), defined by a peak (nucleus), which is frequently a vowel, with consonants clustered around the vowel. Syllables vary from one another in three ways: duration, stress, and tone. Each syllable comprises a syllabic segment, usually a vowel, and most syllables have non-syllabic segments, consonants, before and after the syllabic segment. The syllabic component is the midpoint or nucleus of the syllable and the consonant or consonants that precede the nucleus are the onset of the syllable, with consonant or consonants that follow the nucleus have been termed as coda of the syllable (De Jong, 2004).

The specific admixture of vowels and consonants evolved syllables (a unit of organisation of the sequence of speech sounds, characteristically composed of a vowel nucleus with optional initial and final margins of consonants), the seemingly building premise of a meaningful word (De Jong, 2004). Syllables are often taken to be phonological building units of words, modulating the rhythm, prosody, poetic meter, and stress patterns of a language (Ingram,

1999). The perceptron neural mechanism of the Human Mind relating to the production of phonemes sounds can be captured and recorded non-invasively by Event-Related Potentials (ERPs) as characteristic distinctive neural waveform (varying in time and space) response, that is time- and space-locked to a specific stimulus. The ERPs have further been categorised and segregated on the timeline as exogenous and endogenous waveforms (Polich, 2012). The present study was designed to examine the signature differential P300 waveform response to familiar and unfamiliar stimuli (Sutton et al., 1965).

It has been observed that P300 waveform amplitude is enhanced when participating subjects consciously dedicate added willful effort to a specific target non-familiar infrequent stimulus-task, suggesting the premise that amplitude enhancement of the P300 waveform in response to an alien and/or new stimuli is reflective of reallocation of neural resources along the specific dedicated trappings of attentional and memory contrivances and accoutrements, forming an integral part of underlying cognitive neural dynamics (Isreal et al., 1980), and a familiar and learned stimulus would evoke a truncated P300 amplitude. The present study took advantage of such a distinctive differential P300 waveform response in an attempt to search for a specific paradigmatic pattern along the panoramic neurolinguistic stochastic trajectorial landscape.

Anatomical and functional networks in animal studies have supported a dual-stream context for speech processing (Hickok & Poeppel, 2000, 2004; Rauschecker & Scott, 2009) segregated into a ventral stream and a dorsal stream. The ventral stream travels from the auditory cortex in the direction of the anterior temporal lobe and over the uncinate fasciculus into the ventral inferior frontal gyrus (IFG). The dorsal stream proceeds from the auditory cortex along the arcuate fasciculus, through the parietal lobe, and into the dorsal premotor cortex.

Numerous studies of neuroimaging have examined the brain regions supporting phoneme processing. Rimol et al. (2005) used fMRI to study activity for consonant-vowel (CV) syllables and stop consonants as compared to a noise control state and documented an increased activation for both consonants and syllables in the posterior superior temporal sulcus (STS) and middle temporal gyrus (MTG) bilaterally, with a laterality preference for larger activity in the left hemisphere.

It is imperative to highlight that activity perceived for phonemes in STS (and ventral portion) is classically localised and focused through the neural lens of STS as compared to the dispersed and diffused response of auditory regions to non-speech (noise) stimuli (Hall et al., 2002). This adheres to a computational hierarchical order for auditory processing in which learned representations for example, phonemes are not stored in the primary auditory

cortex, but in association areas of the human brain, apparently permitting for added flexibility in the representation of relationships amongst low-level features (Chang et al., 2010).

Subsequently, it was concluded that neural processing subservient to phoneme involves regions inclusive of the superior temporal sulcus (STS)/superior temporal gyrus (STG), supramarginal gyrus, and inferior frontal gyrus (IFG). The phoneme identifier seems to reside in Broadman Area (BA) 42, and identification of word form seems to be executed by the posterior portion of STG. The identification of word categories is supported by the anterior portion of STG, i.e., the planum polare, which together with the inferior portion of BA 44 is responsible for an on-line syntactic structure building in real-time (Friederici, 2002). Chang et al. reported in 2010 the finding that consonants from the same phonemic categories did not elicit a differential neural dynamical response on the ERP waveforms, supporting the premise that distinctive neurally patterned networks profile the manner of articulatory response specific to and sensitive to a consonant.

Mesgarani et al. (2014) documented spatial response selectivity at respective electroencephalographic (EEG) electrodes, to characteristic distinctive phonetic features while evaluating the ERP response during natural, continuous speech, inclusive of the entire English phonetic inventory, in the high-density direct cortical surface recordings protocol in human subjects, substantiating the fact that the primacy of multiple cues/spectra of phonetic features is neurally integrated and fine-tuned non-linearly.

Kovács et al. (2017) further detailed that phonemes from the same class exhibit similar ERP profiles with variance in scalp distribution and latency range of ERPs across differential consonants. The latter are correlated with differences in the manner of articulation of respective consonants, ushering in the new doctrine for the linguistic approach of phoneme classification with distinctive patterned neural dynamics. Mehler et al. in 1988 substantiated that oddball research paradigm have an inherent ability to evince salience of categorical phoneme perception for individual and corresponding phonemes. The above findings of morphological and neural dynamical studies further support the premise the dedicated distributed neuronal pools/neural networks with acoustic-phonetic neural signatures seem to be housed within the human superior temporal gyrus (STG).

The synthesis of the above studies led to designing of the present study with the primal aim to evaluate the signature neural dynamics of P300 ERP waveform (representative of endogenous associative cognitive neural processing) in terms of amplitude and latency across different consonant phonetic categories of plosives, affricatives, fricatives, liquids and nasals when compared with each other (inter-phoneme) and when compared within each phonetic

categories (intra-phoneme) across varied spatial electroencephalographic (EEG) leads pairs namely, of frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) regions. To observe constancy of the phonemic milieu, three syllabic CVCVCV non-words with fixed first syllable test, consonant being in the second syllable eliciting the ERP response, were made use of in the present research protocol.

2. METHOD

The current cross-sectional comparative study was carried out in the Department of Physiology at S.M.S. Medical College and Attached Hospitals (Jaipur Rajasthan, India), after obtaining the necessary approval from the institution's research review board and ethics committee (IRRB and EC approval numbers, 23533, 101/MC/EC2020 dated 10/06/2020, 01/02/2021 respectively). Thirty healthy young, with an average age of 20.3 years and a standard deviation of 2.4 years, educated Indian adults from the local community, (English language being the primary medium of instruction in school and college education) participated in the study (right-handed participants with 27 males and 3 females). However, data from four participants could not be included in the data analysis and was subsequently excluded due to excessive noise in the data.

2.1 The stimuli algorithm protocol

The choice of categorical phonemes was based on the qualia of speech sounds segregated as either voiced or voiceless (also known as unvoiced) that are closely involved in prosodic variations of tone, intonation, and stress. The vowel phonemes are primarily voiced, and the underlying neural dynamics (neurophysiological processing) silhouette the articulatory singularity responsible for vocal cord vibration induced specific sound and on the other hand, voicelessness phenomenology involves the diction of sounds in the absence of vibration of the larynx apparatus (Kreidler, 1997; Smith, 2000). The phenomenology of differential neural dynamical processes recruited for voiced and voiceless sounds was made use of in the present study wherein, only unvoiced/voiceless consonants were made use of since voiced consonants produce vocal cord vibrations that at times could represent an admixture mimicking vowel sound (in the process), as apprehended in the second syllable of CVCVCV nonsense words. It is usually assumed that the two sounds so heard namely, voiced or unvoiced (due to vibration or non-vibration phenomenology of vocal

cords during articulation), correspond to speech wave spectra of harmonic or inharmonic, respectively. Taking voicing as the sole criterion of what a listener recognizes when he/she listens to speech, it is observed that harmonic speech waves are indeed often heard as voiced sounds and inharmonic sound waves as unvoiced ones. It is possible, however, to find examples where these relations do not hold and an inharmonic speech wave is perceived as a voiced speech sound (Denes, 1955).

Trisyllabic non-words were constructed using English phonemes with the CVCVCV transposition. The experimental algorithmic protocol was designed in English as the medium of instruction for the participants who had been in English since their school education and the primal aim of the present study was to assess the differential neural dynamics across varied consonant classes. The first syllable always began with the /kE/ sound, which provides a precise start to the words due to its impulse-like onset, and the second syllable consisted of a consonant selected from five different phoneme classes based on the manner of articulation, namely, unvoiced plosives of /p/, /t/, /k/, unvoiced affricatives of /tʃ/, unvoiced fricatives: /f/, /θ/, /s/, /ʃ/, /h/, liquids of /l/, /r/ and nasals of /m/, /n/, /ŋ/. Further to the research dictum, one half of CVCVCV non-words had the vowel /u/ in the second syllable, while the other half had the vowel /i/. Eighty-four non-words were constructed with the third syllable consisting of a nasal consonant (either /mO/, /nO/, or /ŋO/ appearing with equal probability) followed by /O/. Additionally, another 28 non-words had the final syllable /tO/. The non-words were recorded by a native Indian adult male speaker speaking in a neutral style in a soundproof room, using Boat Bass 102 in-ear wired earphones with a microphone. The average word length was 641.4 ms, with a standard deviation of 53.3 ms.

Such a specific stimulus algorithm was designed considering the premise that continuous speech signals are phonetically analysed by segmenting and categorising them into phonetic and sub-phonetic units. A listener must first break the continuous stream of sound into recognisable units to process natural speech. The exercise of segmenting the speech signal into phonetic units is supported by the fact that untrained human beings seem able to execute the segmentation, with languages that such individuals themselves speak and are well-conversant, and perhaps even with languages with which such candidates are not familiar (Roach et al., 1990).

The phenomenology of abrupt changes in speech segmentation is utilised by the human mind (functional human brain), characterised by distinctive articulatory gestures, employed for speech segmentation and parsing. Such a qualified ERP paradigm creates a working measurement of speech segmentation that is suitable for listeners of all ages and backgrounds and is based on the proposed premise of distributed neuronal pools/networks with segmentation and/or modular design for human speech.

2.2 Procedure

The experiment was conducted in an acoustically attenuated, dimly lit room. The participants were seated on a wooden chair, and sounds were delivered through Boat Bass Heads 102 in-ear wired earphones. The participants were instructed to minimise all motor movements and maintain eye contact with a fixation cross displayed at the centre of a monitor in front of them to minimise eye blinks. The experimental set-up consisted of two conditions: a passive listening condition (contestants had no task beyond keeping their eyes on the fixation cross), followed by an active listening condition, when the participants were instructed to press a response key for non-words ending with “/tO/” Each condition consisted of four blocks of 98 non-words each (84 words with a nasal consonant and 14 with /t/ in the final syllable), for a total of 392 non-words per condition. The 84 non-words ending with a nasal consonant appeared four times each, while the non-words ending with “/tO/” appeared twice each in a single block.

The arrangement of non-words was pseudo-randomized with restrictions to ensure that no two non-words with the same middle syllable consonant category followed each other and that non-words with middle syllables of “/i/” and “/u/” were mixed randomly across blocks without subsequent repetition. Each non-word was delivered with a stimulus onset asynchrony fixed at 2000 milliseconds, resulting in 26.1 minutes of stimulation time per condition (i.e., 4 passive or 4 active blocks). Brief pauses were introduced between stimulus blocks with a longer pause between the two conditions (together with clarification of the active task) at the request of the participants. The entire experimental session, including electrode mounting and removal, lasted for approximately 45 minutes.

The EEG data was recorded and analysed using the Brain Electro Scan System (BESS) and software version 4.0 (Axxonet Systems Technologies Ltd., India), and Ag/AgCl surface electrodes were soaked in saline for 24 hours prior to the start of the experiment. Nine electrodes were secured on the participant’s head using a silicon bracket cap, in accordance with the International 10/20 System at F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4. The reference electrode was placed on the left earlobe, and the ground electrode was positioned on the forehead. To ensure accurate data acquisition, the electrode impedances were kept below 20kΩ and the electrical signals were amplified. The EEG recordings were filtered using a bandpass filter of 0.5 to 45Hz and notch filters of 50Hz and 60Hz to remove electrical line noise and smoothing of the waveform. The EEG was digitised at a sampling rate of 1024Hz, and a baseline EEG was recorded for a few minutes before the actual data acquisition started. Eye blinks and other artefacts were removed manually based on visual inspection. The ERP data was analysed using the BESS (Brain Electro Scan System) software

version 4.0 (Axxonet Systems Technologies Ltd, India).

Epochs of 1100 milliseconds in duration were extracted from the continuous EEG recording for ERP analysis. The trigger points for the epochs were selected so that the trigger point was set to the start of the coded event, marking the onset of each stimulus (i.e., 100 milliseconds before the start of the syllable stimulus). The epochs were baselined by taking the average voltage of the period between the syllable start and the 100 milliseconds prior. Visual artefacts in the ERP epochs were removed manually. The ERPs were then averaged across the active and passive conditions according to predefined bins: once for the phoneme categories of the second syllable's consonant (collapsing across the /i/ and /u/ vowel varieties of the syllable), and similarly once for each individual consonant of the second syllable (again collapsing among the two vowel variations of the second syllable). Group averages were created by taking the average across all participants. The data was analyzed and modelled through Statistical Package for the Social Sciences (SPSS) v.22 (1.0.0.1406) software for Windows. The frequency data was analysed using a student's paired t-test, and the amplitude data was analysed using a Mann-Whitney test for comparison between the means of the same sample. A p -value <0.05 was considered statistically significant.

3. RESULTS

The data of 26 subjects with an age range of 18-25 years and a mean age of 20.3 years (standard deviation = 2.3) and male to female ratio of 7.6:1 with audio stimulus of CVCVCV patterned trisyllabic non-words was analyzed.

3.1 Comparison of P300 waveform amplitude

The comparative evaluation of P300 amplitude (μ V) across different EEG channels in the frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) regions did not elicit significant difference (p -value $> .05$) in inter-phoneme classes of plosives, affricatives, fricatives, liquids, and nasals, though significant differences in inter-phoneme classes of fricatives and nasals inter-phoneme classes could be appreciated in the parietal region of P3 ($p = .006$) electrode site (Figure 1). Moreover, on comparative analysis of phonemes within the same categories (intra-phoneme categories such as plosives, affricatives, and liquids), significant differences in P300 waveform amplitude could be appreciated within the intra-phoneme classes (Figure 2 and 3) of fricatives and nasals at parietal (P3) electrode ($p = .006$) only, more specifically

on qualified assessment of fricative \int vs. fricate f at C3 ($p = .023$), fricate θ and \int at C3 ($p = .002$) and C4 ($p = .027$), fricate s and \int at C3 ($p = .009$) and C4 ($p = .042$), and fricate \int and h at C3 ($p = .035$) EEG electrode sites, and for nasals m and η at the parietal region P3 electrode site, ($p = .037$) [the said EEG electrode leads being a window to underlying designate distributed neuronal pools of speech areas] (Table 1).

Table 1. The comparative analysis of P300 wave form amplitude (μV) across different EEG channels through inter-phoneme and intra-phoneme categories

Phoneme Classes	Significant change in amplitude (μV) of P300 wave form in EEG leads		
	Frontal	Central	Parietal
Fricates vs. Nasals	-	-	P3 ($p = .006$)
Fricates \int vs. f	-	C3 ($p = .023$)	-
Fricates θ vs. \int	-	C4 ($p = .027$), C3 ($p = .002$)	-
Fricates s vs. \int	-	C4 ($p = .042$), C3 ($p = .009$)	-
Fricates \int vs. h	-	C3 ($p = .035$)	-
Nasal η vs. m	-	-	P3 ($p = .037$)

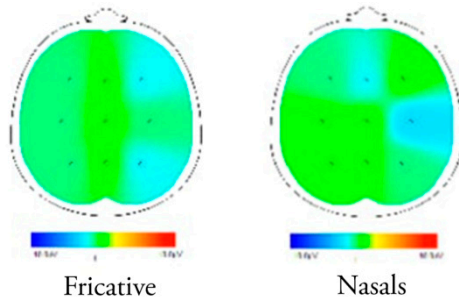


Figure 1. Head maps of significant change in amplitude (μV) of P300 waveform between different class of phonemes (Fricative vs. Nasals)

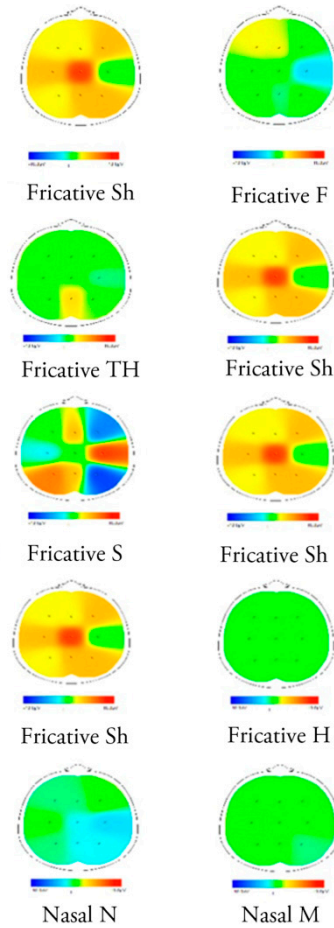


Figure 2. Head maps of amplitude (μV) of P300 waveform between same class of phonemes (fricatives *f* vs. *f*, fricatives *θ* vs. *f*, fricatives *s* vs. *f*, fricatives *f* vs. *h*, nasal *ŋ* vs. *m*)

3.2 Comparison of P300 waveform latency

The ERP P300 waveform latency response to inter-phoneme categories of plosives, affricatives, fricatives, liquids, and nasals exhibited significant differences in latency between (Figure 3) plosives and fricatives at the frontal (F4) electrode ($p = .012$), liquids and plosives at Central (C4) electrode ($p = .028$), affricatives and fricatives at parietal (P4) electrode ($p = .019$), liquids and affricatives at

Central (C4) electrode ($p = .021$), nasals and affricatives at Central (Cz) electrode ($p = .014$), liquids and fricatives at Frontal (F4) ($p = .023$), Central [Cz ($p = .027$), C4 ($p = .003$)], and Parietal (P4) electrodes ($p = .010$), and nasals and fricatives at Frontal (F4) ($p = .035$), Central [Cz ($p = .006$), C4 ($p = .039$)], and Parietal (P4) electrodes ($p = .033$), though no significant differences could be appreciated in P300 waveform latency between the consonants pairs of plosives and affricatives, plosives and nasals, and liquids and nasals.

The P300 waveform latency, on comparative exploration within the intra-phoneme categories of plosives (p, t, k), affricative (C), fricatives (f, θ, s, ʃ, h), liquids (l, r), and nasals (n, m, ŋ), significant differences could be appreciated in the latency within fricatives, liquids and nasals with the patterned differences being appreciated between fricatives s and θ at the Frontal (F4) electrode ($p = .030$), fricative ʃ and θ at Frontal (F4) electrode ($p = .030$) and fricative ʃ and h at Central (C3) electrode ($p = .049$). Significant differences could also be appreciated in P300 waveform latency, when comparatively assessed between liquids r and l at the central (C3) ($p = .015$), Pz ($p = .002$) and Parietal (P4) electrodes ($p = .021$), and between nasals m and n at Parietal (P3) electrode ($p = .050$). However, such a skewed differential pattern could not be appreciated across other intra-phoneme categorical representations (p value $> .05$) used in the present experimental design (Table 2).

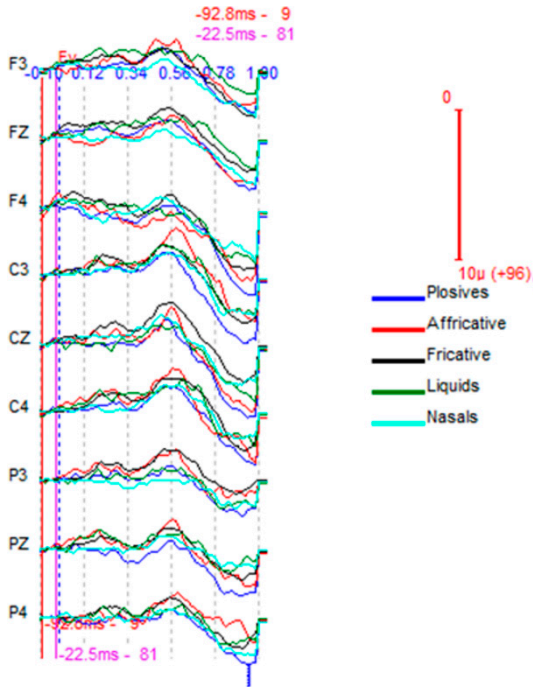


Figure 3. Shows the ERP responses elicited by trisyllabic CVCVCV non-words of different inter-phoneme categories

Table 2. The comparative analysis of P300 wave latency (ms) across different EEG channels through inter-phoneme and intra-phoneme categories

Phoneme Classes	Significant change in latency (ms) of P300 Wave form in EEG leads		
	Frontal	Central	Parietal
Plosives vs. Fricates	F4 ($p = .012$)	-	-
Liquids vs. Plosives	-	C4 ($p = .028$)	-
Affricate vs. Fricates	-	-	P4 ($p = .019$)
Liquids vs. Affricate	-	C4 ($p = .021$)	-
Nasals vs. Affricate	-	Cz ($p = .014$)	-
Liquids vs. Fricates	F4 ($p = .023$)	Cz ($p = .027$), C4 ($p = .003$)	P4 ($p = .010$)
Nasals vs. Fricates	F4 ($p = .035$)	Cz ($p = .006$), C4 ($p = .039$)	P4 ($p = .033$)
Fricates s vs. θ	F4 ($p = .030$)	-	-
Fricates ʃ vs. θ	F4 ($p = .030$)	-	-
Fricates ʃ vs. h	-	C3 ($p = .049$)	-
Liquid r vs. l	-	C3 ($p = .015$)	Pz ($p = .002$), P4 ($p = .021$)
Nasal n vs. m	-	-	P3 ($p = .050$)

3.3 Comparison in laterality of P300 waveform amplitude and latency

The laterality preference for initiating the P300 waveform could be observed for liquids across C4 and C3 EEG electrodes ($p = .012$), and for nasals m ($p = .014$) and plosive p across C3 and C4 electrodes ($p = .040$), though such a patterned neural dynamical response could not be appreciated in P300 waveform amplitude between inter-phoneme categories (p -value $> .05$), except for plosive k that registered significant increase in P300 waveform amplitude at F4 electrode vs. F3 electrode ($p = .040$).

4. DISCUSSION

The present study was undertaken to appreciate the underlying patterned neural dynamics by analysing P300 waveform amplitude and latency in healthy young Indian adults conversant and proficient in both Hindi and English. The experimental algorithmic protocol was designed in English since the medium of

instruction for all participants had been English since their school education and the present study was designed to assess the differential neural dynamics across varied consonants classes. The frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) electroencephalographic (EEG) lead pairs regions, primarily involved in neural processing of language, were assessed for comparative analysis of P300 waveform amplitude and latency across differential inter-phonemes and intra-phonemes consonant phonemes categorization and hemispheric laterality across corresponding frontal, central, and parietal EEG lead pairs. The consistency and constancy of the phonemic environment were ensured by a run of an experimental protocol of three syllabic CVCVCV non-words with a fixed first syllable design and an event-related potential (ERP) of P300 waveform to consonant in the second syllable, which was acquired and assessed accordingly.

Such a research protocol was designed to appreciate the underlying neural dynamics subserving language as assessed through EEG and ERP waveform patterns. Language, a structured means of communication unique to humans, is thought to have evolved through the generation of phonemes, distinctive units of sound that differentiate one word from another. These phonemes have been segregated and categorised into vowels and consonants, the building blocks of all languages. It is believed that vowels, which require simpler and more homogenous neural resources, evolved first in the human maturation stage, followed by the emergence of consonants, which recruit more complex and labyrinthine neural mechanisms (Stark, 1980).

The vowels and consonants represent the primordial plasma for the evolution of a structured, sustainable, credible and incorruptible/incorrigible means of communication in the form of language and the specific dedicated admix of vowels and consonants initiate the phenomenology of recognizable and legible meaningful words that induce a combinatorial pattern impulse generation within the recruited neuronal pools, specific and sensitive for that meaningful word. Vowels, especially the extreme of vowels i.e., “a” “o” and “u” precede consonants on the maturational timeline of language development in infants, since vowels, produced through lip movements, recruit simplistic neurolinguistics dynamics (Hochmann et al., 2011).

In the present study, the façade of “fricatives” and “nasal” consonant phonemes stimuli sketched differential laterality, mirroring a significantly increased P300 waveform amplitude evinced along left parietal EEG electrode of P3 and such a skewed ERP response seems to be signature of hemispheric lateralization, with Broca’s and Wernicke’s area being dominant in an area that is opposite to that of the dominant hand (left hemisphere in right-handed individuals and vice versa), though such functional lateralization in semantics, intonation, accentuation and prosody is not appreciable (Riès et al., 2016). The

vowel in the select non-word syllable, utilised in the present study, inducing cross modalities associative cognitive neural processing, could have trended the distinctive patterned fricative and nasal phonemes of the peaked P300 waveform across the EEG lead pair of P3, differentiating and categorising the said two phonemes neurodynamically and neurospectrally, an observation that refutes the findings of Kovács et al. (2017), who have documented similar ERP neural dynamical response to phonemes belonging to the same class.

The above chronical of P300 waveform amplitude and latency variates so documented suggest a response of the working human mind patterned in the form of a differential spiked P300 waveform when the stimulus of categorised select non-voiced consonants and non-word syllables inter and intra-phoneme impinges on the ongoing dynamical reverberating stochastic trajectory of the human mind (Dube, 2011; Dube et al., 2021). The select preferential response of the spiked P300 wave form to the categorised non-voiced consonants and non-word syllables could eventually evolve a neural signature specific to the underlying contingent neural dynamical processes of attentional relocation along with memory matching and retrieval (Dube, 2011; Dube et al., 2021).

It would be worthwhile to mention that the significant decrease so observed in latency of P300 waveform genesis perhaps reflects the characteristic features of the respective stimuli-locked premise of dedicated neuronal pools for the select categorical phonemes. These latency changes suggest ERP patterning of P300 waveform along such select locations of EEG electrodes sites represent the self-iterating organisation of neuronal pools (fractals) mirroring phonological representation of aforementioned phonemic categories along the stochastic trajectorial phase-space of the working Human Mind in real-time.

Mesgarani et al. in 2014 used high-density direct cortical surface recordings in human participants while they listened to natural, continuous speech to the representation of the entire English phonetic inventory and documented response selectivity to distinct phonetic features at single electrodes with such phonetic features being directly tuned to spectro-temporal acoustic cues, encoded in nonlinear fashion or integrated with multiple cues. The finding of Mesgarani et al. (2014) further supports the premise of acoustic-phonetic illustration of speech having distributed neuronal pools/neural networks across the superior temporal gyrus (STG).

Khalighinejad et al. (2017) observed that EEG responses to continuous speech reliably encode phonetic and speaker distinctions at multiple time intervals relative to the onset of the phonemes. They observed that there are three significant time intervals of 50-90ms (positive deflection), 100-160ms (negative deflection) and 190-210ms (positive deflection), which they called Phoneme Related Potentials (PRP) and were distributed across broad electrodes, spiking maximally at frontocentral electrodes. It was further

documented that hierarchical clustering divulges diverse tiers of alliance conforming to differential phonetic features, the first tier differentiating obstruent from sonorant phonemes (Ladefoged & Johnson, 2010). Within the obstruent tier, a second tier further distinguishes categories grounded on the manner of articulation, where plosives fashioned a distinctive group from that of the fricative phoneme class. The place of articulation seems to be in the lower tiers/rungs of the hierarchy, separating high vowels from low vowels. In general, the clustering analysis of phoneme-related potentials (PRPs) has shown that manner of articulation seems to be the dominant feature stated in the responses, followed by place of articulation, particularly for vowels.

A representative spiked (enhanced peaked amplitude) P300 waveform indicative of synced neural dynamics of cognitive processes of attention and memory for specific inter-phoneme and intra-phoneme categorical representations of language seems to be a specific signature to the said constructs of language under evaluation. In other words, the working human mind assesses and evolves its signature response, which is specific and sensitive to P300 waveform amplitude changes as the type of phoneme is presented and processed.

The modular fractal neural architectonics, exemplified by categorical representation in the form of significant decreased latency and/or increased amplitude, suggests and supports the modular functioning of the human mind, which underscores the premise of fractal non-linear behaviour of underlying neural dynamics. This feature is mirrored by the dedicated neuronal pool at the frontal region, wherein the frontal association neuronal network seems to be activated earlier on the timeline (significant decreased latency for plosives vs. fricative), similarly for liquids vs. plosives and liquids vs. affricatives (with staggered spatial correlates, Table 2) across the central association neural network. A similar patterned response was observed at P4 for affricate vs. fricatives in both comparative analyses of liquids vs. fricatives and nasals vs. fricatives at the same F4, Cz, C4 and P4 EEG electrode pairs, intra-phoneme categories of liquid r vs. l at C3, Pz, P4 and nasal n vs. m at P3, epitomizing the modular fractal neural architectonics of underlying neuronal pools. Similarly, the fractal neuronal pools along frontal association areas seem to be recruited for plosives vs. fricatives, liquids vs. fricatives, nasals vs. fricatives, and in intra-phoneme categories for fricative s vs. θ and fricative ʃ vs. θ, suggesting a plausible inherent preference or a predilection (beating rhythm) of fractal frontal association neuronal pools with intrinsic innate rhyming neural architecture for phoneme pairs of plosives vs. fricatives, liquids vs. fricatives, nasals vs. fricatives, fricative s vs. θ and fricative ʃ vs. θ. Such a fractal proclivity could be appreciated along Central EEG lead areas of association, recruited and conscripted for inter-phoneme categories of liquids vs. plosives, liquids vs. affricate, nasals vs. affricate, liquids vs. fricatives, nasals vs. fricatives and for

intra-phoneme categories of fricatives *f* vs. *h* and liquid *r* vs. *l*. Subsequently, it seems that the fractal architectonic neuronal pool regions of the frontal, central, and parietal areas monograph the significant changes of combinatorial latency and amplitude distinctive for the respective phoneme classes so studied. Henceforth, the characteristic neural dynamic features specific to fricatives, liquids, and nasals seem to etch a categorical P300 waveform across its timeline and amplitude along the stochastic trajectorial phase-space of the working human mind, with the spectre of fricative phonemes having the ability to warp the timeline for the genesis of the P300 waveform.

The singular and fractal P300 waveforms could form potential candidates for detection of the neural signature of phoneme categorization in the field of neurolinguistics, which could act as a probable nidus and platform for the development of the hierarchical fractal algorithm needed in the domain of brain-computer interface (BCI), an offshoot of machine learning and artificial intelligence. The segregation and categorisation of constituent letters of any language into vowels and consonants (during its evolution and growth through phonemic environment) on the basis of the way movements of cheeks, lips, tongue supplanted by diaphragmatic mechanisms and the respective place principle of oro-pharynx, profiling the constituent letters [vowels and consonants], phonemes, syllables, words, phrase and sentence and determine their orderly placement giving rise to a meaningful word, forms the basis of an evolved vocal apparatus syncing with the evolving and progressing neural dynamical features paving way for such a developed, viable, reproducible and valid means of communication, language, in Humans and in this direction, the present study elucidated and re-affirmed the fractal, modular architectonics of neural processing of language, the prescience hallmark of working Human Mind.

5. LIMITATIONS

The present study could assess only right-handed individuals, and explorative assessment with a similar design on left-handed individuals would further give an exciting panoramic view of the neural dynamics of the working human mind in real-time. Moreover, the ERP waveform response to inter-phoneme and intra-phoneme classes needs further exploration to profile the pattern recognition of the respective phoneme classes.

6. FUTURE PERSPECTIVE

The P300 waveform could be employed as an interesting non-invasive tool for the recognition of the neural signature of categorical phonemes (vis-à-vis tell-tale signs of spoken language) as described by the linguists evolving further the discipline of brain computer interface. The phonological processing of phonemes through the P300 waveform feature detectors of amplitude and latency may provide useful insight into the underlying neural mechanisms, providing the platform for pattern generation in the phonological processing of phonemes.

Disclosure statement

The data that support the findings of this study are available on request from the corresponding author, (Dr.Ramesh Chand Choudhary). The data are not publicly available due to the privacy restrictions of the participants.

Conflict of interest

Corresponding author and co-authors do not have a conflict of interest to disclose.

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