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RESEARCH ARTICLE

Lexical tonal discrimination in Zapotec children. A study of the theta rhythm

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KEYWORDS

Tonal-languages;
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Electroencephalogram;
Theta rhythm;
Theta relative power

Abstract

Background: Zapotec is a language used mainly in the state of Oaxaca in Mexico of tonal characteristic; homophone words with difference in fundamental frequency with different meanings. Our objective was to analyze changes in the electroencephalographic (EEG) theta rhythm during word discrimination of lexical tonal bi-syllabic homophone word samples of Zapotec.

Methods: We employed electroencephalography analysis during lexical tonal discrimination in 12 healthy subjects 9–16 years of age.

Results: We observed an increase in theta relative power between lexical discrimination and at rest eyes-open state in right temporal site. We also observed several significant intra- and inter-hemispheric correlations in several scalp sites, mainly in left fronto-temporal and right temporal areas when subjects were performing lexical discrimination.

Conclusions: Our data suggest more engagement of neural networks of the right hemisphere are involved in Zapotec language discrimination.

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PALABRAS CLAVE

Lenguajes tonales;
Zapoteco;
Discriminación tonal
léxica;
Electroencefalograma;
Ritmo theta;

Discriminación tonal léxica en niños zapotecas. Un estudio del ritmo theta

Resumen

Introducción: El zapoteco es un lenguaje hablado principalmente en el estado de Oaxaca, en México, que tiene la característica de ser tonal; es decir, las palabras homófonas que difieren en la altura del fundamental tienen diferente significado. El objetivo de este trabajo fue analizar los cambios del ritmo theta del electroencefalograma en el curso de la discriminación de palabras bisilábicas homófonas en zapoteco.

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Potencia relativa theta

Método: Se empleó el análisis espectral del electroencefalograma durante la discriminación tonal léxica del lenguaje zapoteco en 12 niños sanos de 9-16 años.

Resultados: Se observó una mayor potencia relativa theta en la región temporal derecha durante la discriminación léxica en comparación con el registro de reposo-ojos abiertos. También se observaron varias correlaciones significativas intra e interhemisféricas con predominio entre la región frontotemporal izquierda y temporal derecha mientras se realizaba la discriminación tonal léxica.

Conclusión: Estos resultados sugieren que hay un mayor compromiso de las redes neuronales en el hemisferio derecho que participan en la discriminación del lenguaje zapoteco.

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1. Introduction

Analysis of non-tonal languages depends on different neural circuits formed by heritage and experience during early childhood and engage mainly temporal and frontal areas of the left hemisphere.¹ In tonal languages, discrimination of homophone words depends on pitch of fundamental frequency for lexical meaning. Lateralization for phonetic and semantic analysis has been investigated in adult native speakers of Mandarin. Magneto-encephalography (MEG) recordings indicate that hemispheric asymmetry in temporal and temporo-parietal regions was reduced during sensory processing discrimination of words.² However, to date, no studies have been undertaken looking for brain lateralization in Zapotec.

The Zapotec language belongs to an ancient linguistic family of tonal-language group spoken in Mexico and called Otomangueans. At present, Zapotec language is in danger of extinction; thus, there is an urgent need to study its neurophysiological characteristics. As in other tonal-languages, lexical meanings are established when the word sounds are contrasted with the direction of the F0. Inter-syllabic excursions among homophone words are taught to infants and children in Zapotec homes and schools. It was postulated that at some time during development an originally bilateral activation of several brain areas by lexical-tone perception would be lateralized to one or the other hemisphere;³ however, this fact is unknown.

Techniques for assessing brain organization include functional magnetic resonance image (fMRI) and electroencephalography (EEG) among others. EEG recordings allow the assessment of synchronized neuronal activities for analysis in the frequency domain. Theta rhythm of the EEG has been related to several cognitive processes such as language processing,⁴ auditory perception,⁵ and others. Thus, our objective in this investigation was to analyze changes in the theta rhythm in several areas in the course of word lexical tonal discrimination (LTD) of bi-syllabic word samples of Zapotec spoken in Oaxaca, Mexico.

2. Methods

2.1. Subjects

We studied six healthy female and six healthy male children from an elementary school (age range 9-11 years) and

six healthy female and six healthy male teenagers from a high school (age range 12-16 years) from Juchitán City. Clinical, neurological, audiometric and visual tests were performed in all subjects and did not reveal alterations. All subjects were right-handed according to the Edinburgh questionnaire⁶ and attended school in classes conducted in Zapotec along with some conducted in Spanish, but the subjects were functionally monolingual native speakers. Children and their parents were informed about the research objectives and signed informed consent according to the Helsinki Declaration. The Research and Ethics Committees approved the protocol.

2.2. Zapotec-language test samples

Zapotec speech samples were recorded at the Acoustics Laboratory of the Center for Applied Sciences and Technological Development and at the Psychoacoustics and Phonetics Laboratory of the National School of Music (National University of Mexico). An adult native Zapotec speaker who was a teacher and commentator at a local radio station (with adequate and very understandable speech) provided the samples and the translation into Zapotec of the instructions for the psychological and psychoacoustic tests. Samples were presented in free-field in a quiet room utilizing a Sony cassette recorder and player with a comfortable sound level (between 55 and 65 dB).

2.3. Psychological tests

We used the Free Human Figure Drawing test to measure cognitive and emotional maturation.⁷ Raven Colored Progressive Matrices for Children was employed for testing general non-verbal intelligence in children from the elementary school.⁸ The Rey-Osterrieth Test of Copying and Reproducing Complex Geometric Figures⁹ and the Raven Standard Progressive Matrices Test¹⁰ were utilized for testing visual perception, long-term visual memory, and general intelligence, respectively, in the group of high-school subjects. Subjects were tested one by one while comfortably seated. Results were evaluated by a certified psychologist.

2.4. Psychoacoustic tests

LTD test was utilized.¹¹ The test consists of two parts related to the discrimination and perception of lexical tones of

Zapotec. F0 may go up, down, or remain steady between the syllables of a word. When there was F0 excursion contrast between homophone words, these tones provided each word with a meaning. Bisyllabic words were selected because these are common in Zapotec. They are simple, used in psychoacoustics tests, and eliminate the word length effect (see Appendix 1). In the first part of the test, five pairs of homophone words were presented. In each pair, both words either contrast or do not contrast in the direction of lexical tone movement between syllables. The subject must discriminate either the differences or similarities present and write their response as "up", "down" or "not" on a paper form. In the second subtest, ten isolated bisyllabic words were presented. The subject must perceive whether the direction of lexical tone movement is upward or downward between the syllables of each word and write this on paper.

2.5. EEG analysis

Twenty-four channel EEG equipment was employed (Vector, Buenos Aires, Argentina). We utilized the 10-20 international system for electrode location. All impedances were <5 Kiloohms. EEG was recorded from the Fp1, F3, C3, P3, O1, Fp2, F4, C4, P4, O2, F7, T3, T5, F8, T4, T6, Fz and Cz sites. Band pass filters were set between 0.25 and 30 c/sec as described elsewhere.¹² Theta relative power (TRP) (4-8 Hz) of each standard EEG brain lead was calculated. Afterward, we calculated the average of TRP for either left and right frontal superior locations (F3 and C3, F4 and C4, respectively), left and right frontal inferior sites (F7, F8, respectively), left and right temporal locations (T3 and T5, T4 and T6, respectively), and left and right parieto-occipital sites (P3 and O1, P4 and O2, respectively), as described elsewhere¹³ following international recommendations.¹⁴ EEG recordings were obtained under three conditions: at first, at-rest activity with eyes-closed, in second place, with eyes-open, and, third place while children performed LTD task. We used 1,200 msec epochs, free-of-movements and respiratory and cardiac artifacts. We synchronized the LTD test to the EEG recording. Only trials with correct responses were included in the analysis.

2.6. Statistical analysis

Average and standard deviation (SD) were calculated for continuous variables. Percentages were obtained for binomial variables. Comparisons between results in the psychoacoustics test were made using the Wilcoxon Mann-Whitney test. EEG data comparisons were performed using two-tailed Student *t* test for independent groups. We calculated specific intra- and inter-hemispheric sites correlations by means of the Pearson method as an index of cortical network synchronicity. Bonferroni method was used to correct the possible inflation due to multiple calculations. In this case, to accept results as significant a $p \leq 0.005$ level ($p = 0.05$, Bonferroni corrected) was utilized for accepting differences and associations as significant.

3. Results

3.1. General data, psychological and psychoacoustic tests

The mean age of the children in the sample was 11 years (SD=5 years). One half of the children were male (50%). Mean performance in the Raven progressive matrices test was 33.65 points (SD=6.73), whereas in the Human Figure Drawing 42.00 (SD=8.4) in the Rey-Osterrieth test this was 32.6 (SD=8.8). All data fell within average-to-low values for Mexican children and youths.¹⁵ The LTD average was 72.38 (SD=2.3).

3.2. TRP at rest eyes-open and LTD performance comparison

TRP at rest eyes-open activity fell within averages values for normative populations of this age range (see Table 1).^{12,13} TRP during LTD performance was similar to average values obtained from control populations during the reading (see Table 2).¹⁶ Comparison of the TRP at rest eyes-open

Table 1 Theta relative power at rest (eyes open) prior to stimulation at different sites in children participating in the sample.

Site	Minimum	Maximum	Mean	SD
LFI	4.00	32.50	18.70	8.30
LFS	6.50	36.50	21.87	9.83
LT	3.50	28.00	18.41	8.40
LPO	6.00	45.50	21.75	10.57
RFI	8.00	28.50	19.41	7.19
RFS	6.00	37.00	22.25	9.21
RT	5.50	31.50	17.45	7.39
RPO	6.50	41.50	20.91	8.65

SD, standard deviation; LFI, left frontal inferior; LFS, left frontal superior; LT, left temporal; LPO, left parieto-occipital; RFI, right frontal inferior; RFS, right frontal superior; RT, right temporal; RPO, right parieto-occipital.

Table 2 Theta relative power during lexical tone discrimination at different sites in children participating in the sample.

Site	Minimum	Maximum	Mean	SD
LFI	12.00	37.00	23.12	7.27
LFS	11.50	45.50	25.83	10.74
LT	8.50	33.00	20.79	8.62
LPO	10.00	35.00	23.37	7.37
RFI	15.00	38.50	23.83	7.91
RFS	16.50	36.50	26.08	5.90
RT	9.50	36.50	22.75	7.62
RPO	11.00	39.00	23.04	8.77

SD, standard deviation; LFI, left frontal inferior; LFS, left frontal superior; LT, left temporal; LPO, left parieto-occipital; RFI, right frontal inferior; RFS, right frontal superior; RT, right temporal; RPO, right parieto-occipital.

with TRP while performing the LTD task showed a significant difference at the RT site ($t = 5.5$, $p = 0.01$).

3.3. EEG activity correlations during LTD task

We observed significant correlations in inter- and intra-hemispheric measurements in TRP in different scalp locations during LTD as follows: between LFI site and LT site ($r = 0.76$, $p = 0.04$), LFI and RFS site ($r = 0.79$, $p = 0.02$), and LFI and RT site ($r = 0.80$, $p = 0.02$), LFI and LFS site ($r = 0.83$, $p = 0.01$), LFS and LPO site ($r = 0.83$, $p = 0.01$), LFS and LT ($r = 0.83$, $p = 0.01$), LFS and RT ($r = 0.83$, $p = 0.01$) sites. Scalp distribution of these correlations showed predominance for left frontal sites and right temporal site (Fig. 1). An example of significant correlations is shown in Figure 2.

4. Discussion

4.1. Main findings

Our main findings in this study were that significant differences were found in TRP while performing LTD in RT site, and a wide distribution of TRP inter- and intrahemispheric correlations was found in cortical sites in Zapotec-speaking children with a predominance in left fronto-temporal and right temporal regions. Data showed evidence that the left fronto-temporal network was related with motor and sensory language processing, and the right temporal network was associated with auditory perception and were engaged with LTD in Zapotec-speaking subjects. This finding showed a differential EEG organization associated to Zapotec discrimination and was reported here for the first time.

4.2. Comparison with other studies

The role of the left hemisphere frontal and temporal areas in non-tonal language processing has been known since many years ago.¹⁷ As can be expected from experiences in research carried out in other tonal-languages using other techniques, we observed engagement of language-related neural networks in the left hemisphere and auditory temporal area of the right hemisphere.

In one study, authors compared performance of Mandarin word recognition between Chinese and English subjects. Researchers found increased activation in fMRI in left-sided frontal, parietal, and temporal regions. Within-group comparisons showed that frontal and parietal activities vary for each sub-syllabic components; in the frontal lobe, the Chinese group showed bilateral activation of the anterior middle frontal gyrus for rhymes and tones; within group comparisons of consonants, rhymes, and tones showed that rhymes induced greater activation in the left posterior middle frontal gyrus.¹⁸ Although the observation was carried out using other techniques, our results are in partial agreement, showing the engagement of the right and left hemisphere for tonal language processing.

In a PET (positron emission tomography) study, other researchers compared lexical tone perception of Mandarin and English speakers. They observed that both groups showed common regions of CBF (cerebral blood flow)

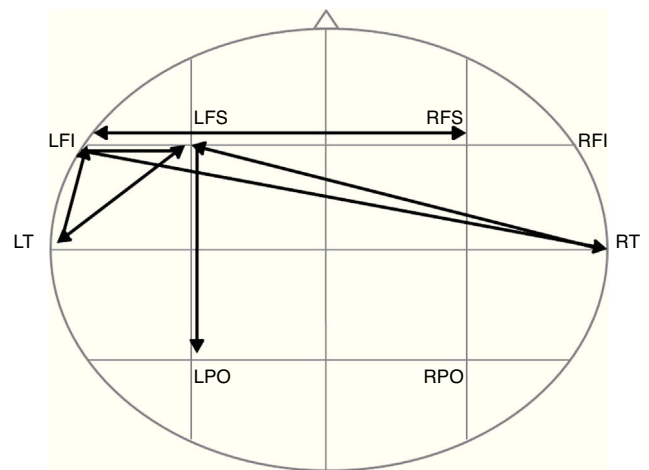


Figure 1 Scalp distribution of significant correlations of the theta relative power (TRP) during the lexical tone discrimination (LTD) in Zapotec. Left fronto-temporal (LFT) and right temporal (RT) sites engaged in the task are evident. LFI, left frontal inferior; LFS, left frontal superior; LT, left temporal; LPO, left parieto-occipital; RFI, right frontal inferior; RFS, right frontal superior; RT, right temporal; RPO, right parieto-occipital.

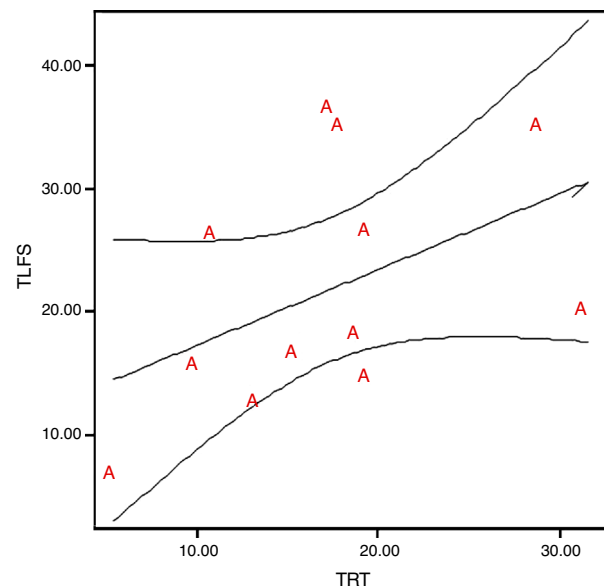


Figure 2 Typical scattergram of correlation of the theta relative power (TRP) at left frontal superior (TLFS) and theta right temporal (TRT) sites. A significant positive correlation is evident.

increase, but only Mandarin speakers showed additional activation in frontal, parietal, and parieto-occipital regions of the left hemisphere. In contrast, the English group showed activity in the right inferior frontal cortex, consistent with its significant role in pitch perception.¹⁹

4.3. Electrophysiological studies in tonal languages

There are few studies that search for specific language lateralization in subjects who speak a tonal language by mean

of electrophysiological techniques. One previously quoted study performed MEG observations in search of the brain lateralization for phonetic and semantic analysis carried out in adult native speakers of Mandarin. Data showed an activation of bilateral temporal and temporo-parietal regions indicating that the degree of hemispheric asymmetry was reduced during the discrimination of a word stimuli.² This result suggested an increased participation of right hemispheric regions in spoken word recognition in Mandarin and are in partial agreement with our results.

Lou et al. demonstrated that early auditory processing of lexical tone at a pre-attentive stage is lateralized to the right hemisphere in a tonal language.²⁰ Researchers presented to Mandarin speakers meaningful words with a consonant-vowel structure and infrequently varied either its lexical tone or initial consonant using an odd-ball paradigm to create a contrast that resulted in a change in word meaning. The lexical tone contrast evoked a stronger pre-attentive response as revealed by the mismatch negativity (MMN) being greater in the right than in the left hemisphere, whereas consonant contrast produced an opposite pattern. These results are also in partial agreement with those obtained by our team.

Zhang et al. investigated the time course of tonal and orthographic encoding during Mandarin word production.²¹ Participants were shown pictures and carried out a dual-choice Go/noGo decision based on tonal information (whether a picture name was tone 1 or 2, or tone 3 or 4) or orthographic information (whether or not the picture name was written with a left-right structure character). Analyses of N-200 wave effects and lateralized readiness potentials indicated that tonal information was retrieved prior to orthographic information. These results imply that orthographic codes are unlikely to contribute to phonological encoding in the production of the spoken word. A late effect for the N-200 wave in the Go/noGo tone condition was observed, which may be related with the internal self-monitoring of supra-segmental information with the participation of both cerebral hemispheres. Data from this investigation partially support our results, showing the participation of both cerebral hemispheres in language decoding in the case of tonal languages.

Nan et al. performed an ERP (event-related potential) study to examine the neural substrates for pitch processing in music and in tonal language with phrases ending in either congruous or incongruous pitches.²² Female Chinese musicians were chosen as listeners due to their broad exposure to music and a tonal language. Pitch violations in both domains were associated with a frontally distributed late positive component (LPC). In addition to evoking an N-400 wave for language condition, pitch processing as revealed by the LPC was left-lateralized for tonal language and right-lateralized for music. The authors proposed that their data may imply different brain resources engaging in pitch processing depending on whether its function is lexical as in a tonal language such as Chinese or musical in nature.

Zhang et al. examined evidence that supports the categorical perception of Chinese lexical tones at the pre-attentive stage and attentive responses to tonal continua in an ERP experiment that recorded N2b and P3b waves of odd-ball responses.²³ They found that for both the N2b and the P3b component the responses elicited by the

within-category deviants were similar in the left and the right recording sites. However, the across-category deviants elicited larger responses in the left recording sites than in the right sites, reflecting conscious phonological processing of lexical tones. Results provided electrophysiological correlates of the categorical perception of Chinese lexical tones in later stages associated with controlled processes. Despite methodological differences between this and our study, data partially support our results.

Recently, Gu et al. studied the left hemisphere lateralization for lexical and acoustic pitch processing in Cantonese speakers by MMN observations.²⁴ They found that the MMN elicited by lexical pitch contrast was lateralized to the left hemisphere, which is consistent with the pattern of function-dependent brain asymmetry, in non-tonal language speakers. However, elicited by acoustic pitch contrast was also left hemisphere lateralized and was inconsistent with the acoustic-dependent brain asymmetry. This finding was explained due to the fact that Cantonese phonology is more complicated than Mandarin. For this reason, left hemisphere developed an evolutionary adaptation for perception of a higher amount of tone variations for each word. EEG coherence pattern associated with Cantonese also was investigated to determine if higher interhemispheric coherence was possible to find in Cantonese reading. Results revealed that reading was generally associated with higher theta coherence than the resting condition and English reading; specifically theta coherence showed an increased intra-hemispheric connection in the left hemisphere and inter-hemispheric connections over the temporal, central, and parietal/occipital regions compared to English reading.²⁵ In this sense, our results of Zapotec brain-language organization is closer for Mandarin and farther from the Cantonese organization.

4.4. Study limitations

Our study has some limitations in that it was cross-sectional in design instead of a prospective follow-up. The number of cases studied is small. In the future, we must additionally study other specific right-hemisphere activation tasks, i.e., musical discrimination. Finally, we had no neuroimaging correlation; thus, in subsequent studies, we must include fMRI studies to support our observations.

We observed a significant TRP increase at the RT site during LTD in Zapotec and a wide distribution of inter- and intra-hemispheric areas correlations with a predominance at the left fronto-temporal sites and right temporal site, suggesting involvement of these sites in processing the Zapotec language.

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No other funding than participant institutions is declared for this study.

Conflict of interest

The authors declare no conflict of interests.

Appendix 1. Examples of Zapotec words used in the lexical tone discrimination (LTD) test and fundamental contrasts between Zapotec words

Word	Frequency change (Hz)	Duration (msec)	Amplitude change (dB)	Meaning
biuxe	(137/195)	684	−71/−75	small
biuxe	(105/91)	803	−70/−79	it broke
rabi	(156/96)	591	−68/−86	he says
rabi	(128/184)	758	−77/−88	he devours
guidxi	(240/109)	697	−81/−85	village
guidxi	(260/202)	697	−89/−77	abundance

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