NEUROELECTRIC CORRELATES OF A NEUROPSYCHOLOGICAL MODEL OF WORD DECODING AND SEMANTIC PROCESSING IN NORMAL CHILDREN

FEGGY OSTROSKY-SOLÍS, ENRIQUETA CANSECO, SERGIO MENÉSESES, OSCAR PROSPERO and DANIEL ZARABOZO

Universidad Nacional Autónoma de México

and

ALFREDO ARDILA

Instituto Neurológico de Colombia

(Received September 10, 1986)

The use of event-related potentials (ERPs) as a technique in the study of word decoding and semantic processing in the cerebral cortex was investigated. Ten right-handed boys, aged between nine and eleven, with adequate school performance were studied. Visual ERPs were obtained using four derivations: occipital (O₁,O₂) and parietal (P₃,P₄). Four stimuli were presented: a frequently used noun written in capitals; the same noun in handwriting; the pictorial representation of this noun (drawing); and a pattern consisting of a checkerboard (25 squares). The data were analyzed using multivariate procedures. A Principal Component Analysis with varimax rotation of the solution was applied. Concepts about reading contributed by cognitive psychology, neuropsychology and neurophysiological research are reviewed, and a hypothetical model of the neuronal bases underlying the act of reading is presented. This model emphasizes the complex, dynamic interplay of the neural structures involved and points to the differences which probably exist between beginning and fluent readers. The results are discussed in accordance with the proposed model.

Keywords: visual evoked potentials, word processing

One of the most important tasks in the study of brain–behavior relations is to get to know and understand not only where but also how the physiological processes which give rise to complex psychological behavior take place. Given the complexity of the nervous system and of the higher psychological skills such as language, reading and spelling, this objective can, without doubt, only be achieved by means of a combination of methods and concepts belonging to different disciplines, for example: psychology, neurology, physiology and linguistics. As Kirk (1983) points out, the way in which cognitive functions are conceptualized will constrain our capacity to look for and understand the neural mechanisms that subserve them. At the same time, neuropsychological and neurophysiological research can help us refine psychological models by dissecting subtle components of higher psychological functions.

Address for Correspondence: Feggy Ostrosky-Solís, Av. San Bernabe 641-22, Mexico 10200 D.F. Mexico.

We acknowledge the translation of Jenny Lewis and technical assistance of Miguel Angel Guevara.

This research was partially supported by a grant from the Consejo Nacional de Ciencia y Tecnología (CONACYT)—Code PCCSCNA 002122.
Over the past twenty years, theorists in cognitive psychology and psycholinguistics have developed a considerable body of information on language processing (Luria, 1966, 1973; Goodman, 1967; Gibson & Levy, 1975; Johnson & Hook, 1978; Ferreiro & Teberosky, 1980; among others). The individual is seen as an active "information processor" who has multiple modalities of input and output of information, and the potential for a network of complex integrative skills. Language in its oral and written forms is viewed as a complex symbolic skill. Adequate competence and performance requires not only the integrity of basic processes such as perception and memory, but also the learner's active involvement. According to Gibson and Levy (1975), the process of language acquisition is one of learning rules. Initially, the child learns phonological, syntactic, semantic and pragmatic rules for oral communication. Later, when reading is introduced, he abstracts a set of rules related to orthography and the written text.

Reading is the acquisition of information from the written word. The term decoding is used to refer to the process of converting printed language into meaningful, spoken language. Thus, in the process of decoding there are two levels; adequate identification of the word and its comprehension. Identification of a word can be achieved through one or more of four basic techniques: whole word recognition, context, structural analysis and phonetic analysis. Reading strategies for decoding single words are different from the strategies necessary for understanding the meaning of a group of words.

Gibson and Levy (1975) have provided a general theory of reading that emphasizes the developmental changes that occur in the process of reading acquisition. According to their theory, the fundamental unit of visual information in reading is the word. Individual words are composed of different types of distinctive features: graphic features, orthographic regularities in letter combinations, phonological correlates of letter combinations and semantic characteristics of words and groups of words. These constraints form patterns of invariance to which the reader must attend in order to obtain meaning from print. Learning to read involves developing strategies for processing increasingly larger units of information. The type and size of the attribute processed changes at different phases of the reading acquisition process. Beginners attend primarily to the graphical and phonological attributes of the words. More experienced readers attend to syntactic and semantic regularities within connected texts. In part, these changes reflect the child's developing capacity for abstracting meaning from the text.

Neuropsychological Evidence

The complexity of the language processes and the various cognitive skills required for their adequate performance lead to the supposition that whether in its spoken or written form, language performance is not due to just one neuronal system (visual or auditory), but rather to the intervention of a whole working range of specific structures, each of which has a specific bearing on the dynamic whole.

From work based mainly on the study of altered behavior observed among brain damaged patients, research into the field of neuropsychology (Geschwind, 1962, 1965; Luria, 1966, 1973; Gazzaniga & Sperry, 1967; Benson, 1984, 1985) has provided a structural-functional model of language.

For Luria (1966, 1973), for example, reading is a complex behavior effected by means of a complicated functional system of cooperating zones of the cerebral cortex and subcortical structures; since each structure plays a highly specific role,
alterations in reading ability vary according to the particular structure that has been damaged. For example, reading ability can be affected in different ways by lesions of different areas: lesions of the occipital lobes of either hemisphere may result in optic agnosia or visual–perceptual defects; lesions of the left temporal cortex may cause deficits in phonemic discrimination, auditory verbal memory or auditory comprehension; lesions of the occipital–temporal–parietal region of the left hemisphere (angular gyrus) may produce an inability to recode visual stimuli into sound; lesions of the postcentral gyri may result in an inability to articulate sounds when decoding and blending individual phonemes; lesions of the anterior frontal lobes may give rise to an inability to use predictions and confirmation skills when reading; lesions of the medial regions of the frontal lobes may result in poor arousal modulation and an inability to sustain attention to the reading task; lesions of the inferior region of the left premotor region may cause motor speech blending problems.

Similarly, Benson (1984, 1985) and Geschwind (1962, 1965) have proposed that higher cortical functions require the coordinated participation of several brain structures and have described different types of language (oral and written) disturbances with characteristic clinical syndromes and different anatomical substrata.

In his model of brain function, Geschwind (1962, 1965) has emphasized the role of the connections between the functional regions of the brain and their importance in the learning of complex activities. According to his model, behavioral alterations are interpreted in relation not only to the lesions affecting the cortical centers but also to the interruption of the pathways which connect these centers. As a result of the damage to these pathways, it is impossible to transmit information which generally travels from one region to another to be integrated and transformed.

Benson and his associates (Benson & Geschwind, 1969; Benson, 1984, 1985) have described several major acquired reading disturbance syndromes (alexia) that arise from damage to the dominant hemisphere and/or to the splenium of the corpus callosum. These syndromes include:

1) Alexia without agraphia or verbal alexia, associated with the left medial occipital region, involving the splenium, which is characterized by an inability to understand written material without impairment of the ability to write. These patients can write normally, spontaneously or to dictation, but later cannot read what they have written. They may be able to read some numbers and letters.

2) Alexia with agraphia or literal alexia, which is associated with a combined occipital and temporal or parietal lesion, characterized by deficits in both reading and writing, left–right orientation, finger agnosia and mild anomia.

3) Frontal or syntactical alexia, associated with the left inferior premotor region, characterized by an inability to understand the syntactical structures of language and/or to maintain the sequence of words in a sentence.

4) Deep dyslexia or semantic paralexia, followed by massive injury to the left hemisphere language area, characterized by a tendency to substitute one word for another with a related meaning, i.e. “rifle” for “gun,” or “orchestra” for “band.” According to Benson (1984), these semantic paralexic errors suggest a right hemisphere reading.

Reading difficulties associated with right hemisphere lesions have been called spatial alexia (Luria, 1973) and are characterized by a conservation of the ability to read letters, words and short sentences but difficulty in recognizing the information
relevant to spaces in long texts: the patient joins letters belonging to two different words to form a third word; has difficulty with punctuation marks and confuses letters and words as a result of the omission or addition of graphemic strokes.

**Neurophysiological Evidence**

The advance in computer techniques has permitted the development of neurophysiological techniques such as the event related potentials (ERP) which have provided the researcher with a complementary opportunity to understand what is going on in the brain during the activation of different functional systems. As Knight (1985) points out, cognitive processes occur in a time frame measure of milliseconds; up to two and a half correct decisions can be made per second and reaction time can be as fast as 150 milliseconds. Since ERP can measure neural activity occurring within a millisecond time range, they offer the possibility of revealing the sequence and timing of neural events occurring during the activation of specific cognitive activities. ERP are transient voltage fluctuations generated in the brain in conjunction with sensory, motor or cognitive events. They are considered to represent the summation of electric fields with a large number of neurons activated in synchrony. As Harmony (1984) points out, the basic assumption when working with ERPs is that, as a result of the event, an ensemble of neurons functionally related with such an event comes to exhibit a particular spatiotemporal organization, that is, patterns of coherent or coordinate synaptic events will occur in different portions of the brain in a temporal sequence determined by anatomical connections, transmission times and similar parameters of the ensemble.

It has been found that there are at least two sensory systems involved in creating the electrical responses recorded at the scalp. These systems interact to form the various components of the wave. One is a specific, direct projection to the primary sensory areas that evokes a short latency positive–negative wave complex; the other is a nonspecific or indirect system that primarily affects the later components. Stutton et al. (1965) and Wilkinson and Vee (1972) have reported that the early or specific components result from exogenous influences related to the character of the stimulus such as intensity, frequency and patterning. These early components show marked cross-modality variations. The later nonspecific components are described as endogenous and vary according to the state of the subject, the meaning of the stimulus and the information processing demands of the task (Hillyard et al., 1984).

Over the past few years, there has been a great deal of research on the relationship between the ERP and information processing in the brain. These studies have attempted to correlate ERP components with complex psychological variables such as selective attention (the N1), active discrimination of stimulus features (the N2), delivery of task-relevant information (the P300) and expectancy (the CNV). Although not as reliable as these four components, other endogenous brain potentials have been related to several levels of language processing such as phonetics (Wood, 1975; Molfese, 1978, 1980); semantics (Chapman et al., 1980; Brown et al., 1976, 1980; Thatcher, 1977) and syntax (Kutas & Hillyard, 1982). Recently, ERPs have also been applied in the study of reading. A negative wave with a peak-latency of 200–600 ms (N400) occurs when subjects notice semantically deviant words in sentences (Kutas & Hillyard, 1980a, 1980b, 1980c), read unpredictable deviant words (Neville et al., 1982) or name words (Stuss et al., 1982; Sanquist et al., 1980).
Studies with children aged six to twelve have also reported specific late ERP components (300–500 ms) correlated with color discrimination tasks (Kurtzberg et al., 1979), with the visual processing of pictures of cartoons and objects (Symmes & Eisengart, 1971; Neville, 1977) and differentiation between words and nonsense syllables (Shelbourne, 1973).

The use of neurophysiological techniques such as ERPs offers the possibility of identifying the spatial and temporal flow of information that takes place during the activation of different functional systems and might suggest ways in which this flow of information is altered during deficient cognitive processing. The present study seeks to distinguish the characteristics and components of ERPs correlated with word decoding and semantic processing in a group of normal readers. A second paper describes the comparison of these results with the ERPs of a reading disabled group.

MATERIALS AND METHODS

Ten right-handed boys aged between nine and eleven, with adequate school performance were studied. All children were evaluated for adequate sensory acuity (visual and auditory), normal intellectual capacity as measured by the Weschler Intelligence Scale for children, revised form. (Group X Full Scale I.Q. = 108, S.D. = 11.3) and adequate motor development. A standarized psychoeducational battery (Ostrosky et al., 1984) which assesses oral understanding and expression, reading, writing and arithmetic was also applied.

Four stimuli were presented, three of which were physically different, but with the same semantic content: a frequently used noun written in capitals (COCHE – car), the same noun in hand-writing (coche), the pictorial representation of this noun (drawing), and neutral stimulus consisting of a checkerboard (25 squares).

The stimuli were projected onto the centermost part of a white screen placed 1.50 m from the subject’s eyes. They were composed of a blue outline against a black background. Stimuli duration was 100 ms with a variable interstimuli interval of three to six seconds. In each run there was a randomized presentation of 64 stimuli (16 presentations of each stimulus). During one session there were four runs with 64 presentations in each and a rest period after each run.

The subject was seated in a comfortable chair in a dark, electrically shielded and sound-dampened room. He was instructed to keep his eyes focused on the display throughout the whole run. The subject’s task was to observe the words and to report the stimulus presented. A small red light was used as a fixation point. This light was turned on two seconds before stimulus presentation and was turned off two seconds after presentation. At that moment, the subject had to respond, naming the stimulus presented. This response was recorded by a researcher.

The subject’s EEG was recorded from standard Grass electrodes (gold cup shape) attached to the scalp by bentonite CaCl paste. The 10–20 International System (Jasper, 1958) was followed in placing the electrodes utilizing four leads; two occipital (O1 and O2); two parietal (P3 and P4). The reference electrodes were linked mastoids and a ground electrode was placed on the forehead. Inter electrode resistance was maintained below 10,000 kohm. Eye movements were monitored by EOG (electrooculogram) placing electrodes above and below the left lid.

The frequency bandpass of the recording system (Beckman polygraph) was 0.5 to 150 Hz. A Grass Stimulator (s88) generated a synchronization signal for each
stimulus. After amplification by the Polygraph, the signals were recorded on an 8 channel analog tape recorder.

After conducting the experiment, the data stored on the tape were analyzed by signal averaging in a PDP 11/40 digital computer.

The four types of stimuli were identified and averaged separately, eliminating incorrect responses and trials contaminated by eye movements.

Evoked potentials were averaged using 64 points (sample at 8 ms interval). Averaging began 24 ms before stimulus presentation to establish the level of baseline activity, and analysis time lasted 512 ms.

DATA ANALYSIS

In order to determine the minimum number of waveshapes that could account for the variance in the evoked potentials obtained, a Principal Component Analysis (PCA) with Varimax Rotation of the solution was applied. PCA was performed separately for each derivation. The 40 Evoked Potentials (ten subjects x four stimuli) formed a 40 x 64 data input matrix for each lead.

With an eigenvalue equal to or greater than unity in each PCA, ten components accounted on the average for 92% of the total variance. Principal components extracted from the intercorrelation matrix were rotated using the Varimax procedure to increase their distinctiveness while preserving orthogonality. Factor scores or gain scores were computed for each of the 40 original EPs, on each of the ten Varimax principal components. These scores measure the contribution of the components to the individual EP.

The factor scores were tested by one-way analysis of variance to determine if each principal component varied systematically in amplitude as a function of the stimuli characteristics. Tukey-tests for simple effects were used to assess the source of variance in each scalp location. Significance levels were set at .01 (two-tailed test).

RESULTS

Figures 1 and 2 show the grand mean evoked by the four stimuli and the components found to be significant at the occipital leads.

At the left hemisphere, the response to the verbal stimuli (capitals and handwriting) are similar throughout the whole potential and none of the components found by means of the PCA can distinguish them.

The PCA shows that the checkerboard presents a significantly lower latency than the other three stimuli at the 100 ms latency (component 9). In the 154-256 latency range, the verbal stimuli (capitals and handwriting) remain the same, while the drawing and the checkerboard are different (component 10). At the 450 ms latency, (component 1) the evoked response by the checkerboard is significantly different from the three stimuli with the same semantic content (coche in three different physical presentations). At the right occipital lead, the similarity between the evoked responses of the two verbal stimuli (capitals and handwriting) is not so evident as in the left hemisphere. Two components (3 and 4) covering a latency range from 0 to 256 ms distinguish the checkerboard from the drawing and coche in capitals. Component 3 picks up differences between the stimuli at an early latency range, and component 4 has the highest peak at 300 ms latency.
Component 10, peaking at 212 ms, distinguishes the checkerboard from *coche* in capitals.

In summary, at the occipital leads, the waveform evoked by the checkerboard can be distinguished from the three other stimuli. At the right hemisphere, the waveform evoked by the checkerboard is different from that evoked by *coche* in capitals, while, at the left hemisphere, the waveforms evoked by the three stimuli with the same semantic content (*coche* in three different physical presentations) tend to be more similar to one another. The components found at the left occipital lead are more complex than those found at the right occipital.

At the parietal leads (Figures 3 and 4), visual inspection showed that in both the right and left hemispheres a prominent negative peak appears at about 380 ms. At P3 this peak coincides in latency for the three stimuli with the same semantic content (capitals, drawing and handwriting), but only for capitals and handwriting at Pz. At the left parietal lead, the morphologies of the verbal stimuli (capitals and handwriting) are very similar throughout the sweep, and both are very different from the non-verbal stimuli (checkerboard and drawing).

Two middle latency components (component 5 with a peak latency at 204 ms and component 10 with a peak latency at 293 ms) revealed differences in
morphology between the evoked responses elicited by the drawing and the three other stimuli, while component 7, with a peak latency at 385 ms revealed a difference in amplitude which was higher for coche in capitals.

At the right parietal lead, only component 4 with a peak latency at 281 ms, distinguishes between coche in capitals and the evoked response elicited by the drawing.

In summary, the waveforms evoked by coche in capitals and the drawing are distinguished by all the components found to be statistically significant: components 5, 7 and 10 at the left hemisphere and component 4 at the right hemisphere. At the left parietal derivation, the PCA showed a greater number of significant components than at the right parietal.

**Interhemispheric Differences**

An interhemispheric comparison shows various points of interest.

At the occipital leads (Figure 5), visual inspection revealed that the greatest asymmetries are observed in the waveform evoked by the stimuli coche in capitals within a latency range of between 200 and 350 ms. The two verbal stimuli (coche in handwriting and in capitals) show a prominent positive peak at 300 ms, with
VISUAL EVOKED POTENTIALS IN WORD PROCESSING

FIGURE 3 Mean ERPs evoked by the four stimuli at the left parietal lead and components which showed significant differences among stimuli. The arrows show the latency where each component has the maximum peak.

FIGURE 4 Mean ERPs evoked by the four stimuli at the right parietal lead and component which showed significant differences among stimuli. The arrows show the latency where this component has the maximum value.

greater synchrony between hemispheres for coche in handwriting than for coche in capitals. For the drawing, this positive peak occurs at 250 ms.

At the parietal leads (Figure 6), it can be observed that the activity evoked by coche in capitals becomes perfectly synchronous in both hemispheres, showing a high negative peak, almost identical in amplitude at 385 ms.
FIGURE 5  Mean ERPs evoked by each stimulus at the left occipital (solid lines) and right occipital (dotted lines) hemispheres.

FIGURE 6  Mean ERPs evoked by each stimulus in the left parietal (solid lines) and right parietal (dotted lines) hemispheres.
The greatest asymmetries are observed for the waveform evoked by the drawing. At the right parietal lead, a high negative peak appeared and extended within a wide latency range, reaching its maximum voltage at 320 ms. Principal component analysis revealed that a larger number of components distinguish the waveform evoked by the drawing from the other stimuli.

_Coche_ in handwriting presented a synchronous negative peak (also synchronous with the negative peak evoked by _coche_ in capitals) at 385 ms, but with a slightly lower amplitude at the left parietal leads.

**DISCUSSION**

Neuropsychology and neurophysiology have contributed data and theoretical models about the functional and structural organization of higher cognitive functions. Psychological functions and the neural substrata that subserve them are organized, complex, dynamic systems. Different cognitive functions are distributed across a system of synchronously working zones that are differentiated both anatomically and functionally. Thus, cortical organization of higher cognitive functions is viewed in terms of a "System Approach" (Walsh, 1978). This approach combines the concept of cortical connections with that of functional systems. Accordingly, the brain may be considered as a communication network, incorporating multiple information transmitting channels which lead to and from decision points. The points of the system which are most closely aggregated in cerebral space will be those most vulnerable to selective inactivation as a result of focal brain injury. The neurons that constitute a decision point are widely diffused over the cerebral cortex. Their distinctive function, however, depends on their mode of linkage rather than on the physical features of individual neurons.

The application of adult neuropsychological data to children's developmental language processes has been criticized on the basis that it assumes equivalence between the mature performance of an acquired skill and the acquisition of the skill. Apparently, the brain mechanisms involved in acquiring a behavioral skill are not always those that maintain the skill once acquired (Goldberg & Costa, 1981; Dennis, 1983).

Dennis (1983) suggests that a plausible neuropsychological model of reading acquisition would require a coherent developmental account of both brain functions and the different reading operations performed by the beginner and the proficient reader.

In both children and adults word decoding implies at least: (1) knowledge of visual symbols; (2) knowledge of an equivalence system between graphemes and sounds; (3) the possibility to perceive the different graphemes; (4) knowledge of the spatial value and organization in space of the visual symbols system. This, naturally, is connected to all the operations which require recognition of oral language (phonological discrimination, verbal memory, morpholexical associations with visual percepts but not necessarily visual, etc.). However, research in the area of cognitive psychology and psycholinguistics has revealed that for beginning readers, graphological and phonological units are important for word recognition, and visual information must be translated into a speech code in order to obtain meaning (Luria, 1966; Meyer et al., 1974). Advanced stages of word decoding are highly automatized processes, making hardly any use of phonetic analysis and synthesis and in which word recognition can occur directly on the basis of visual information (Doehering, 1976; Vygotsky, 1962).
It seems, then, that for both the beginner and the proficient performer, word decoding takes place by means of a complex interacting system. Cortical regions devoted to the processing of visual (i.e., occipital lobes); auditory (temporal lobes); crossmodal (occipit-tempor-parietal regions); and integrative (frontal regions) information is not different in beginners or advanced performers. What changes are probably the demands placed on different regions and the interaction between them. Thus, during the initial stages of word decoding, there is a high demand on the regions that recode visual stimuli into sounds. Once decoding has become automatic, certain cortical connections are no longer necessary, although they continue to exist potentially and can be reactivated if needed. For example, when we read unfamiliar words or high frequency words with spelling mistakes.

Based on neuropsychological and psycholinguistic research, we propose the following interpretation of our data:

The location of the electrodes in the occipital derivations corresponds to the zone the destruction of which would produce certain visual agnosia and alexia without agraphia. This occipital region, in some way, participates in the recognition and perceptual categorization of visual information. If a subject presents some kind of dysfunction in this occipital area, he will not be able to recognize the image of a car or integrate the letters which form the word coche (car), and even less perform these two operations simultaneously: match the word “car” with an image of a car. In the occipital derivations, we found some components which identified the words presented in different styles of handwriting and others which seem to identify these words with the image of the car (but not with a checkerboard). The first components (verbal components) were situated in the 156–256 ms zone, and the second (semantic components) were observed over 380 ms. This late positive enhancement might be a P300 type effect involving “representational matching” (Hillyard et al., 1971). Late positive ERPs have been elicited in tasks in which a stimulus must be compared with the short-term memory trace of a preceding stimulus. For example, Thatcher (1977) using a delayed semantic matching procedure involving synonym, antonym and semantically neutral words pairs, found a late positive component (latency in the 400–500 ms range) elicited when the second word was a synonym or an antonym. As in our research, this effect was maximum at the left posterior (occipital) region. Chapman et al. (1981) presented a randomized sequence of two numbers and two letters, with either the numbers or the letters designated relevant, and found that the second member of the relevant pair which had to be compared elicited the largest P300 component. Apparently, P300 was triggered upon recognition of stimulus relevance. Working with children aged eight to twelve, Shelbourne (1973) found a late positive component between 450 and 600 ms correlated with the child’s ability to differentiate between words and nonsense syllables.

In relation to the middle latency (154–256 ms) components that we observed at the left occipital leads, Hillyard et al. (1984) reported that when visual stimuli were selected from one another on the basis of certain features (such as colour, concentration or size) a slow endogenous negativity in the latency range 150–350 ms was observed over the posterior scalp. According to this author, this broad negativity appears to represent modality-specific processing that leads to stimuli identification. The stages of stimulus classification that follow the initial selection are reflected in longer latency ERP components (P300).

The sequence of events developed in O1 and P3 is extremely interesting. In O1, a large positive peak appears initially with a slightly lower latency for the checkerboard. This first peak corresponds to the arrival of information about the
stimulus and, in some way, depends on its physical parameters. In an intermediate latency between 156 and 256 ms, there is a high correlation between the two verbal stimuli which become very different from the checkerboard and the drawing and after approximately 380 ms the evoked response of the drawing, while the checkerboard runs independently. Thus, the intermediate latency (identification of the word in capitals and in handwriting) could correspond to verbal recognition and the long latency to semantic recognition.

Angular alexia is a more literal alexia (inability to recognize letters) resulting, on the one hand, from confusion between letters similar in shape (e.g., N and H), due to the spatial relation between strokes and, on the other, a consequence of the difficulty to relate graphemes to phonemes. Thus, the parietal zone is where we achieve a literal recognition of the written language (graphemic recognition). P3 is a zone relatively far from the primary visual area. Therefore, we could expect a relatively high latency for the arrival of the activity set off by the visual stimuli. In our recording, up to approximately 180 ms the activity produced by the four stimuli is shown independently and from there on there is a notable correlation between the two verbal stimuli (coche in capitals and in handwriting), and these two potentials in turn become quite different from the drawing. In some way, the letters must be recognized as such and matched with a sound system (Spanish has almost perfect phonological writing). Semantic recognition (matching the written word and decoding it as a sound sequence with a visual percept) would be relatively late and would suppose (at least in Spanish) initial recognition of each of the letters and conversion into sound (phonemes). This operation would imply the participation of a network of interactions between the occipital, parietal and temporal regions in a way similar to that shown in Figure 7.

**FIGURE 7** Human brain viewed from the left. Shadowed areas correspond to the zones of the literal, verbal and syntactical alexias. Letters denote the main landmarks according to the 10-20 International System for placing electrodes in the left hemisphere. Numbers denote zones activated during word decoding; interconnections between them are indicated. (1) Primary occipital area; (2) angular gyrus; (3) superior temporal circumvolution; (4) secondary occipital area; (5) temporo-occipital region; (6) medial temporal circumvolution.
The shadowed areas in the figure show the critical zones in the appearance of literal alexia (parieto-temporal), verbal alexia (occipital) and syntactical alexia (frontal) (Benson, 1985). Oral recognition of a word would imply the utilization of pathways 3–6 [the superior temporal convolution, which would permit the phonological discrimination of sounds and their categorization. Damage to these pathways would give rise to Luria’s acoustic–agnostic aphasia (1966) or to verbal deafness; the second temporal convolution would permit recognition of the phonological sequence which forms the word and damage would cause acoustic–mnestic aphasia or phonological jargon] and 6–5–4 (4 is an occipital zone which permits unified recognition of the visual percept—its destruction leads to visual agnosia; 5 is the temporo–occipital region—damage here produces amnestic aphasia which implies forgetting the names of visually presented objects and a large number of semantic paraphasias).

Reading would imply recognition of progressively more complex visual strokes in the primary visual area (1); unified perception of these visual strokes in recognizing a pattern which would be a grapheme (2); the existence of a correspondence system between graphemes and phonemes (2–3); the sequencing of graphemes to form a word (4) at the alexia without agraphia zone, and the translation of the written word into an oral word (4–5–6). In alexia without agraphia, a certain holistic reading is possible and could be interpreted as a kind of visual agnosia or simultaneous agnosia, as some authors have proposed (Luria, 1966).

Beginner readers would use the parieto-temporal pathway (1–2–3) in preference for recognizing graphemes and phonologically decoding them. Fluent readers would use more lexical and holographic systems, the occipital-temporal pathway (1–4–5–6).

Reading single words out loud will activate areas of the postcentral and precentral gyrus involved in the articulation of sounds when decoding and blending individual phonemes. The reading of sentences and paragraphs which requires the ability to interpret the relational value of written words, will require the additional activation of left inferior premotor regions.

Reading depends upon the left hemisphere because of that hemisphere’s special capacity for understanding language. However, the right hemisphere is also involved during reading tasks. Thus, normal reading appears to activate both hemispheres (Figure 8).

According to Benson (1984), written words, at least those that are imagable, appear to stimulate the right angular gyrus and from this activity visual images appear. He hypothesized that when a word is visualized not only does an auditory/phonemic interpretation of the word occur (primarily at the left hemisphere), but also a visual image of those words that are imagable will be produced. Semantic paralexia occurs when the patients are unable to perform a direct grapheme–phoneme interpretation as a result of left hemisphere damage and give a logical name (i.e., band) to the image visualized from the written word (i.e., orchestra).

In the present research we found a greater variability in the waveform evoked by the four stimuli at the left hemisphere. That is, more components distinguished the four stimuli. At the occipital leads, the greatest differences were found between the neutral stimuli (checkerboard) and the three stimuli with some semantic content (coche in its three different forms). At the parietal leads, however, the differences were marked between the stimulus coche in capitals and the drawing. It is possible that, for our children, coche in capitals had a higher linguistic content than the same
stimulus in handwriting. Recent studies of the cognitive processes involved in the acquisition of reading support this hypothesis. Using Piaget-type classification tasks with words printed in different types of letters, Ferreiro and Teberosky (1980) have found that children tend to classify words printed in capitals as letters and words printed in handwriting as "drawings". It seems, then, that our children were very active in their processing of each stimulus abstracting and differentiating distinctive features between them.

Research in the fields of cognitive psychology, neuropsychology and neurophysiology has revealed that brain processing during reading is a complex, dynamic phenomenon. The approach that takes into account this complexity and dynamic interplay of neural structures will without doubt further our understanding of where, how and when the processes that lead to adequate reading performance occur.

REFERENCES


