A study of the neurobiological basis to explain the theories of semantic processes (2002-2022)

Un estudio de las bases neurobiológicas para explicar las teorías de los procesos semánticos (2002-2022)

Ana María Flores-Núñez*, Mauro Marino-Jiménez** y Russell Laudrup Casimiro-Dionicio***

ABSTRACT

The study of language, specifically semantic development, has considered the lateralisation of one hemisphere since its discovery by neurologists Paul Broca and Carl Wernicke in the 19th century. However, research conducted in the last decade, based on functional magnetic resonance imaging (fMRI), found that language production and comprehension not only involve the left side of the brain but the eloquent areas may also form a large part of the brain mass. This study presents a brief historical account of the neurobiological study of the semantic processes of homo sapiens, with emphasis on the development of changes in the study of semantic processes theory from 2002 onwards. This work considers the latest research completed by the University of Berkeley (Lescroart and Gallant, 2019), which point out the location of semantic maps in the brain, as well as the most recent studies on the construction of figurative meaning in relation to cultural and social processes.

Keywords: semantics, brain, functional magnetic resonance imaging (fMRI), neurobiology, language.

* Peruana. Magister en Literatura Hispanoamericana de la Pontificia Universidad Católica del Perú. Universidad San Ignacio de Loyola, Lima, Perú. ORCID: 0000-0002-6419-1577, afloresn@usil.edu.pe.
** Peruano. Doctor en Filología de la Universidad Nacional de Educación a Distancia. Universidad San Ignacio de Loyola, Lima, Perú. ORCID: 0000-0003-2541-0447, mmarino@usil.edu.pe.
*** Peruano. Licenciado en Psicología de la Universidad San Ignacio de Loyola. Universidad San Ignacio de Loyola, Lima, Perú. ORCID: 0000-0003-0733-9608, russell.casimiro@usil.pe.
RESUMEN

El estudio del lenguaje, específicamente el desarrollo semántico, ha considerado la lateralización de un hemisferio, desde su descubrimiento por los neurólogos Paul Broca y Carl Wernicke en el siglo XIX. Sin embargo, los estudios de la última década, a partir de la resonancia magnética funcional (RMf), consideran que la producción y comprensión del lenguaje no solo implican el lado izquierdo del cerebro, sino que también las áreas elocuentes se encontrarían conformando gran parte de la masa cerebral. En el presente texto, se hace un breve recuento de lo acontecido en el tiempo, en relación con el estudio neurobiológico de los procesos semánticos del homo sapiens, y se pone énfasis en el desarrollo de los cambios en el estudio de la teoría de los procesos semánticos desde el 2002 hacia adelante. Se considera, en este trabajo, las últimas investigaciones alcanzadas por la universidad de Berkeley (Lescroart y Gallant, 2019) en las que se evidencia la ubicación de los mapas semánticos en el cerebro, y las más recientes sobre la construcción de sentido figurado en relación con los procesos culturales y sociales.

Palabras clave: semántica, cerebro, resonancia magnética funcional (RMf), neurobiología, lenguaje.
Introduction

Language as a systematic process is guided by use and constitutes meaning that makes it possible to achieve processes such as the understanding and interpretation of a statement. This, in addition to the fact that the specificity of human cognition lies in the role of semiotic exchanges, was established through the dynamics of signs and constant adaptation of meanings (Valsiner, 2022). Moreover, logic is part of this conceptualisation, which occurs in a pragmatic and connected way (Capirci et al., 2022). Thus, language uses general cognitive apparatus, whose study requirements are linked to disciplines that complement linguistics.

This variety of processes has linked language studies to those of cognition. This relationship has strengthened over time due to technological advances that have allowed the study of neurological bases with increasing accuracy (Leschziner and Cerulo, 2022). In this sense, it is already possible to observe how the interpretation of situations occurs differently in the human brain, and the text-context structure is identified through it (Davis and Yee, 2021). However, in this proposed reality, the semantic structure is one of the most difficult structures to evidence because the argumentative structure is required to define the idealisation of the concept (Zhou et al., 2021).

From this perspective, the world that appears between the mind and object responds to a series of stimuli in which previous information intervenes, is related to the new one and gives rise to the stated meaning. From this point of view, neural integration is a process that allows neurons to add different excitatory and inhibitory inputs and elaborate a response based on them (Liu et al., 2022). Therefore, the scientific concern about the relationship between cognition and language has led to numerous changes in recent years. This is an important historical development on semantic processes, which can be visibly established, as new perspectives on linguistic studies.

We seek to establish a population genetics study on semantics because, according to recent research, there is enough evidence to include works that determine the idea that the semantic map occupies the whole brain and not only the left laterality as (even currently) claimed in neuro-linguistic studies (De Heer et al., 2017; Lescroart and
A study of the neurobiological basis to explain the theories | Flores-Núñez et al.

Gallant, 2019). This study will be approached as a process of linguistic evolution, from which multiple axioms can be developed, thereby leading towards specialisation in the semantic process.

The ‘linguistic change’ concept consists of the modification and transformation process that all languages undergo in their general historical evolution and the respective linguistic units of each of their levels in particular (Campbell, 2004). Therefore, it is possible to determine how semantics have been shaped in the brain over time. To this end, it will be very useful to understand the processes that can be evidenced, such as metaphor and metonymy, as well as their location in the different lobes and their interhemispheric specialisation.

The central nervous system cannot be understood as a static and uniform system because it is based on a network of electrical currents and biochemical reactions among neurons. This is a synapse process fundamentally established at the cellular level (De la Iglesia-Vayá et al., 2011). Parallely, communication is built on the establishment of meanings that are dynamised by the reactions of the interlocutors. Signs and actions interchange the role of mediation to strengthen communicative effectiveness (Cuetos, 2012). Thus, the semantic system works dynamically and carries out modification processes in the human brain. Therefore, it is essential to establish historical evolution to determine the current state of its study.

Diachronic view of semantics

Meaning has existed since societies began establishing themselves in their most primitive forms. Archaeological elements, such as pieces created at that time or remains of individuals with severe damage to their physiognomy (but preserved for reasonable periods of time), allow us to develop communication awareness, values and reciprocal care actions. An example of the former is mentioned by Henshilwood and Dubreuil (2009) regarding the oldest archaeological evidence of human behaviour and symbolic culture, which dates back to approximately 70,000 years ago, in the Middle Stone Age. This corresponds to engraved ochre pieces and sea shells drilled in the Blombos Cave, South Africa. This process evidenced a shared behaviour of symbolic value in the early community. The second case is goes back 45,000 years’ to the tribe of Shanidar (present-day Iraq) (Scheerenberger,
1984). In that territory, the remains of a man with severe damage in the upper and lower limbs as well as permanent eye and head injuries (including communication problems) were found. However, according to the findings, this individual was able to survive for some time due to the proactive actions of the society that took him in. This shows symbolic value, an understanding of the patient’s condition and attention to his basic needs.

Later, in Greek culture, several references were presented to prove the relationship between the functioning of the brain and language. For example, the first allusion to the loss of language skills due to cranial trauma comes from the writings of Herodotus (484-426 BC), who made a reference to the Egyptian Phrygian language. Therein, the meaning of /békos/ ‘bread’ included the concept of language acquisition (Bonvillian et al., 1997). Here the loss of comprehension capacity was established from encephalo-cranial trauma, which is consistent with the ideas of Democritus (460-370 BC) and the Hippocratic School (460-370 BC) that began associating language disorders with the left hemisphere (Herrera, 2019). This condition was then confirmed as medical science consolidated the relationship between brain function and language (Kong, 2021).

Other cultures sought to establish motor or religious causes for speech and comprehension difficulties. For example, in the works of Confucius (551-479 BC), several postulates related to the ‘cure’ of diseases determined by comprehension problems stand out. For this purpose, they used kinesitherapy (re-education through movement) as a support method for the recovery of language faculties (Bertini, 1971). On the contrary, other cultures, such as the Babylonian and Jewish, signified these conditions as a sanction for undesirable behaviours. Moreover, the well-known Hammurabi Code, dating back to 1750 BC, mentioned that comprehension problems were divine punishment (Hammurabi, 2020). For its part, Deuteronomy 28 (1400 BC) states: “Yahweh will smite you with madness, blindness and disturbance of spirit” (International, 2013). However, this perspective changed with the coming of Jesus because the New Testament relates the problems of understanding to suffering and, consequently, with healing mediated by mercy: ‘Dumb and deaf spirit, I command you, come out of him and enter him no more!’ (Mark, 9, 25); this dates back to 70 AD (Santa Biblia, 2013).
An unexplored reference of the Middle Ages is Augustine of Hippo (354-430 AD). In his books *Principles of Dialectics*, *Confessions* and *On Christian Doctrine* he explored the semantics based on the function of signs and through the understanding of the reality of others (De Hipona, 2009). He anticipated the distinction between the forms with which the value of words is evoked and understood it, thereby establishing a relationship between rhetoric and dialectics (Laborda, 2019). This expansion of semantics was reflected in the history of literature with topics such as love, as a disease or the nature of imagination. For example, the Archpriest of Hita (1283-1350) sought to alleviate affectionate anguish through *The Book of Good Love*. Shakespeare (1564-1616) rhetorically questioned whether the main input of creativity comes from the head or heart in *The Merchant of Venice*.

During the 17th and 18th centuries, several milestones regarding the construction of meaning were achieved. One of these was the contribution from the Port Royal school, with the work of Arnauld (1612-1694) and Lancelot (1615-1695) (1997), which made distinctions between the processes of conceiving, judging and reasoning as ways to establish the awareness of languages. Thus, they established a methodological change in language learning, which at that time in history was based on repetition and memory. However, Locke (1632-1704) (2005) systematised the semantic theses by emphasising the conception of an ‘idea’ as opposed to that of ‘situation’, that is, the construction of meaning from the mind of individuals (from conception to interpretation), rather than from specific circumstances.

Another significant example was that of Leibniz (1646-1716) (2016), who argued that language transcends the morphological dimension to become involved in understanding, knowledge and the construction of reality. In this way, the latter complemented the abstract vision of the former to return to the signs that the sensible world establishes in the conception of ideas. These proposals were complemented by authors such as Condillac (1714-1780) (1999) and Humboldt (1767-1835) (1991) regarding the construction of thought through language and the influence of personal conceptions on this process.

The 19th century was marked by the contribution of neurology with the participation of Broca (1824-1880) (1861) and Wernicke (1848-1905) (1874). Broca’s finding was based on the close relation-
ship between the left hemisphere (Brodmann’s areas 44 and 45) and verbal production. In turn, the latter discovered a type of aphasia linked to comprehension, which is also located in the left side of the brain (Brodmann’s area 22). Both contributions, revolutionary and consistent with health programmes and rehabilitation therapies, underwent a further complication, which can be seen till date: the belief that only left lateralisation is involved in language development (Rutten, 2022).

Many studies on semantics were conducted during the 20th century, constituting an evolution for semantics, models and methodological approaches. Saussure, for example, pioneered the paradigm of the sign as a dyad, composed of the signifier and the signified (Saussure, 1916). Therefore, the phonetic element will be associated with the concept linked to it, which is already in the mind of the speaker (De Angelis, 2022). Another significant example is by the researchers of the Prague Circle. They found, among other contributions, the idea of partial belonging of individual consciousness within collective ones due to the social nature of the communicative process. Besides being an attribute for the study of meaning, this also constitutes an opening towards the interdisciplinary nature of modern linguistics, including social sciences and literature (Gallardo, 2010; Ibrahim and Plecháč, 2014; Kořenský, 2017).

Another significant example is provided by cognitive semantics, developed by authors such as Lakoff and Johnson (1980). This approach, still under development, specifies the importance of metaphor and metonymy for shaping the structure of thought at the individual or collective level. Thus, the positions, hierarchies and structures formed by these figures are established as a core part of language and their nature is confirmed at different levels: awareness, structure and thought. The biological basis (which allows for the development of skills linked to meaning) paves the way for a semantic structure with inputs from the outside world and the conception and interpretation related to it.

The resources obtained for the study of semantics from linguistics and neurology are diverse. However, the strengthening of the interdisciplinary nature, achieved since the 21st century, calls for a different section to establish proposals.
Contemporary semantics: new perspectives to be developed

The historical framework on semantics produces a multidimensional result. Although paradigms have been formed with increasing depth and reflection, the persistence of the link between linguistic and cognitive processes, the biological basis for oral and written production and the social influence on communicative activity is plausible. For these reasons, reflexively formulated theories can be physiologically confirmed. Just as the first indications of this postulate were present in prehistoric times, in later years this knowledge was formalised through many findings. However, the discoveries of Broca and Wernicke during the 19th century, the development of sign semantics as belonging to a social environment and the rediscovery of the figurative in the 20th century represent a gateway to greater scientific and technological development, which has made it possible to establish new chapters on linguistics in the early 21st century.

The various processes carried out by the brain, including the logical-semantic one, involve an aspect known as semantic memory. This is part of one’s own knowledge of the world, which is recorded transversally in the events of one’s own life. That is where the memory and use of words lie, and they are considered part of a database to construct meanings (Cuetos, 2012). In this sense, semantic memory also corresponds to a way of processing categories, such as time and space (Colás-Blanco et al., 2022).

Faced with such a situation, it is worth asking about the process of studying the semantic variations produced at the intracerebral level, wherein it is possible to identify that the variations are aspects related to any other proposed utterance. This challenges the idea of a functional specialisation, in which a brain region has specific tasks. In fact, multiple studies have determined that the different regions of the brain establish communication and interconnection in their processes, that is, rather than functional specialisation, it is a functional integration (De la Iglesia-Vayá et al., 2011). This is consistent with the idea that brain functioning is globally restricted or enhanced in individuals with certain trauma, disorders or apparently unrelated clinical conditions (Matar et al., 2022).

The application of this position has been developed in the early 21st century by using functional magnetic resonance imaging (fMRI) and
determining lateralisation in speakers who had suffered aphasia in the lexical decision test, as evidenced by dominance in the left and right hemispheres (Figure 1) (Álvarez-Linera et al., 2002).

Figure 1.
Functional magnetic resonance imaging (fMRI) for hemispheric activity in lexical decision making. Source: Álvarez-Linera et al. (2002).

This result is confirmed by Avila (2003), whose analysed case of grade I astrocytoma (a type of cancer) in the left temporal region and history of epileptic seizures determined that the lateralisation of language functions responded to the right hemisphere, contrary to what had been believed until then regarding the left lateralisation in Broca’s and Wernicke’s areas. This result, which confirms the plasticity of the brain in case of anomaly or impairment, is consistent in subsequent studies.

Fernández (2003) mentions two key evidences to talk about memory. The first is that the semantic content of the assumptions generated by a stimulus affects reasoning. Human beings become used to assuming facts and solving problems adaptively rather than logically, considering the abstract when it is really necessary. The second is that people tend to act in a stereotypical way when it comes to processing frequently confronted representations. Therefore, similar stimuli generate repetitive responses.

Therefore, semantic processes are completely associated with reasoning in an abstract or concrete manner. The communicative situation
and physical conditions determine significant modifications in cognitive processes. This is also confirmed in the study conducted by Patiño (2007) regarding aphasic patients whose semantic memory had been altered due to herpes simplex encephalitis. The disorder associated with problems in the left temporal lobe was related to the knowledge of non-living things or their use (for example, tools). Moreover, in studies conducted with patients who presented deficits in connotation or metaphorical aspects, the location of the involved eloquent areas was focused in the right hemisphere. Thus, while comprehension actions may be complementarily housed in both hemispheres, the type of processing performed to process meaning operates in a completely different manner.

Huth et al. (2012) developed a study on semantics based on fMRI. This work, processing thousands of objects and categories, opposes the theory that these are clustered in a certain area of the brain. Therefore, their processing is established continuously as a kind of semantic map along the entire cortical surface. This is confirmed in the brain activity before 1,705 objects and categories were shown to the study groups in films, which evidenced gradients according to the stimulus and whose activity is corroborated in different individuals.

Figure 2.  
This form of graphic representation is significant because it clearly shows the right and left hemispheres in the use of semantic relations and how neural activation occurs within the entire cerebral cortex. After this study, it was observed that the points of coincidence of the subjects involved were the same, considering that the speakers used the same language as in a standard register.

A continuation in this field of study is the work developed by the same team in 2016 (Huth et al., 2016). They elaborate on how meanings are represented as a semantic system in the regions of the cerebral cortex. However, an important part of the selectivity is still unknown. It has been possible to analyse the stimulus in several individuals, and its consistency can be affirmed in all of them. For this reason, domains linked to ideas, categories and the conformation of what is represented are maintained.

This case, studying a sample of seven individuals, aimed to map how the brain represents the meaning (semantic content) of language. The novelty of this study is that it was not carried out with isolated words but with real stories of people whose voices were perceived by the study subjects. Thus, it was possible to create what scientists at the University of Berkeley called a *semantic atlas of the brain*, through which nearly all regions of the brain are activated.

This information should be complemented, considering that we are dealing with semantic comprehension, not production processing. According to Huth et al. (2016), the resulting maps show how semantic information is represented in a set of patterns linked to several regions of the cerebral cortex. Each of these is selected for particular types of semantic information: people, numbers, visual properties or places. Many of these details are similar among people.

Another finding of this experiment is the rate of semantic prediction of the subjects because, during the development of the stories, it was possible to observe the activation of large regions of the cerebral cortex (Figure 3).
The areas shaded with different colours correspond to the activation of the cerebral cortex. The atlas created by the developed semantic system responds to the different colours that activate different areas. For example, all parts highlighted in red indicate the semantic elements that respond to the social aspect, the pink-shaded area responds to the emotional aspect and so on.

The result shows a detailed map of how meaning is represented through the cortex, which can be directly observed for the first time. It is not limited to a few areas of the brain, as had been stated until the first decade of the 21st century with the discoveries by Broca and Wernicke (left lateralisation); rather, meaning is coupled in broad regions of the brain, occupying almost every part of it. Bilaterality is another observed and corroborated concept. Finally, it can be confirmed that these representations are highly bilateral: the responses of the right cerebral hemisphere and those of the left hemisphere harbour a similar number and size (Huth et al., 2016).

Thus, in view of this situation, the dogma about left lateralisation in language production comes to an end. Understand it entails a statement in which it can be observed that the activation of brain areas occurs in both hemispheres as stated in the introduction. However,
further studies point out that, in addition to terms or categories, it is possible to determine the brain’s understanding of space management, such as distance and openness (Lescroart and Gallant, 2019).

Interdisciplinarity in meaning studies is also on the rise through social aspects, the use of figurative language and emotional implications (Tseng and Chuang, 2022). Brain linkages, which are globally associated with stimuli, are also found to be inscribed at the individual (physiological flexibility) and social (linguistic construction and binding values) levels. For these reasons, the influence of phenomena, such as cultural comprehension in terms understanding one’s own language, translating words from another or assuming certain values, is recurrent (Kalda, 2022). Similarly, evolutionary consistency, associated with physiological stimuli when addressing certain issues, has fixed forms of representation in the fMRI, and in studies of linguistic behaviour, which are evident in the ways human beings use, build and develop new meanings (Berman et al., 2022; Paramita et al., 2022).

Conclusions
The historical evolution of semantic studies has determined constant variables in the construction, transformation and creation of meaning. Thus, there is a clear correspondence between the empirical bases of historical and contemporary studies that build meaning based on the functioning of different parts of the brain. Moreover, hierarchical relationships are established between neural stimuli and certain themes, the categorisation of senses and the strengthening of metaphorical meanings for common purposes in human society. For these reasons, the development of the semantic map is a product not only confirmed in groups of individuals, but is also the result of evolution and a way of configuring complex processes of cerebral interconnection.

Contemporary linguistics must resort to more interdisciplinary studies to address the different phenomena it investigates. Increasingly, neurology, translation, computational support and literature, among others, are available to verify and combine a wide spectrum of possibilities. The construction of meaning, communicative phenomena, etc., is a way to combine the physiological, social and cultural bases in the human being as well as a method to create research applications for new models of development.
References


Colás-Blanco, I., Michoe, J., La Corte, V., & Piolino, P. (2022). The role of temporal distance of the events on the spatiotemporal dynamics of mental time travel to one’s personal past and future. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-05902-8


A study of the neurobiological basis to explain the theories | Flores-Núñez et al.


Saussure, F. (1916). Course in *General Linguistics*


Zhou, P., Critchley, H., Garfinkel, S., & Gao, Y. (2021). The conceptualisation of emotions across cultures: A model based on in-