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Outside the ‘Core System’

Embodiment of Meaning and the Motor Cortex

B.A. Essay

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Abstract

The identification of the mechanism underlying the brain-language relationship is crucial for the study of language, and for the understanding of fundamental aspects of human cognition. The traditional view of the relationship between the brain and language is based on the idea that the particular functions of language are served by particular areas of language processing. This view was supported by the study of cases of acquired aphasia and the associated brain autopsies. With the development of advanced technologies allowing the study of language in the living brain, our understanding of the neurological foundation of language was revolutionised. A new outlook on language behaviour suggests that the relationship between the brain and language is far more complex than the traditional model implies. The contemporary theory of embodiment cognition predicts the importance of the motor cortex in language comprehension, by showing in a sophisticated way how cognition is grounded in specific neurological structures of the physical processing mechanism. However brain and language studies are surrounded, to this day, by conflicting opinions regarding the functional role of the motor areas in language comprehension. Thus, the aim of this thesis is to confirm the statement that motor areas of the brain functionally participate in the comprehension of word meanings by enhancing the effect of the semantic processing of language. The thesis reports on the results of two relevant studies: "Primary motor cortex functionally contributes to language comprehension: An online rTMS study" (Vukovic, Feurra, Shpektor, Myachykov & Shtyrov, 2017) and "Abstract semantics in the motor system? An event-related fMRI study on passive reading of semantic word categories carrying abstract emotional and mental meaning" (Dreyer & Pulvermüller, 2018), which provide compelling evidence of how motor areas of the brain participate in the processing of action-related words and subcategories of abstract nouns.

Keywords: language comprehension, motor cortex, embodiment, action-related words, semantics of abstract nouns

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1. Introduction

Some of the fundamental questions philosophers and scientists have asked themselves since the distant past relate to the nature of human cognition and the remarkable language capacity human beings share. What happens in our minds when we speak, and what happens when we listen to another person? How do we understand spoken ideas, and how does the brain relate a word to its meaning? Where exactly is language located in our brains, and what kind of relationship is there between language and the brain? Until recently, most of the knowledge concerning the brain-language connection was based on the relationship between behaviours in patients with aphasia and autopsy studies of associated brain lesions. According to most of these studies, semantic properties of language are linked to Wernicke’s area. In the past three decades, our understanding of language in the brain has been revolutionised by modern advanced techniques which allow the study of language processing in the living brain. The modern findings suggest that the relationship between the brain and language is far more complex than previously thought.

Of particular interest is the current controversy concerning the functional role of the motor cortex in semantic processing. According to the classical view of the localisation of linguistic functions in the brain, one would not expect semantic processing to be linked to an area primarily involved in control of the physical body. Although the traditional model of language processing highlights the importance of Wernicke’s area in language comprehension, this thesis argues in favour of the claim that the mechanism underlying semantic processing is grounded in the basic biological functions of the body, and that therefore language understanding is directly linked to the motor structure of the brain along with the primary language areas. This argument is supported by compelling evidence for how action-related words and a significant subcategory of abstract nouns are linked to motor areas of the brain.

Broadly speaking, in order to highlight the evidence for the functional role of the motor cortex, this thesis embraces a psycholinguistic and neurobiological approach to the study of language processing and the comprehension of meaning. Section 2 provides a brief overview of the most important clinical and theoretical studies of the nineteenth century relating to the understanding of the relationship between the brain and language. Section 3 offers for consideration the evolution of the classical model of language and discusses the gaps in, and controversy surrounding, the anatomical and functional features related to the classical model, with a focus on Wernicke's area and semantic processing. This section also introduces the modern advanced techniques which are used in the studies of language processing in the living brain, and provides a brief overview of the contemporary findings related to them. In section 4, the increased evidence for the causal role of the motor cortex in semantic processing is demonstrated by reviewing two recently-conducted studies performed with two types of modern techniques which enable the examination of the causal role of the motor cortex in the 'real-time' processing of language. In the first study (Vukovic et al., 2017), the researchers investigate behavioural reactions to action-related words, with lexical decision and semantic judgment tasks, during *repetitive transcranial magnetic stimulation* (rTMS) of the primary motor cortex. In the second study (Dreyer & Pulvermüller, 2018), the authors assessed the functional role of the motor areas of the brain in language comprehension using *functional magnetic resonance imaging* (fMRI) techniques during the passive reading of subcategories of concrete words and abstract nouns.

These studies provide compelling evidence in support of the theory that motor areas of the cerebral cortex, in addition to the traditional language areas of the brain, functionally contribute to the comprehension of word meanings. This leads to the conclusion that the classical model of language oversimplifies our understanding of the mechanism underlying semantic processing, and overestimates the gap between language comprehension and the body. The current findings can be linked to potential new knowledge of language processing, and fundamentally new types of therapy for people with language impairment.

2. The Discovery of Language in the Brain: Aphasia Studies

The first significant advances in the localisation of language in the brain were made in the late 19th century, based on the study of aphasia, a language disorder resulting from brain damage. However, before the invention of neuroimaging technologies in the 1970s, the only way to study brain lesions and language pathology related to this kind of damage was by means of autopsy (Libben, 2011, p. 460). The brain autopsy examinations were often carried out in hospitals, after the careful observation of patients' behaviour whilst they were still alive, in order to identify a connection between their behaviour and various types of brain damage. The main goal of such studies in the context of language processing was to determine which areas of the brain were damaged and how that damage affected particular language functions. Based on autopsy studies and observed deficits of language in patients with brain damage, it was concluded that particular functions of language were processed by particular areas of the brain. This knowledge allowed the assumption that semantics is served by Wernicke's area.

The famous discovery of specific language areas in the brain is found in the pioneering works of the French neurologist Paul Broca and the German physiologist Karl Wernicke (Libben, 2011, pp. 455-476). In 1860, in a Paris hospital, Broca observed a patient who had experienced severe language deficits over a long period of time. The patient was unable to speak but appeared to understand when others spoke. Subsequently, the autopsy of this patient's brain appeared to show neurological damage in the inferior area of the frontal lobe of the left hemisphere (Libben, 2011, p. 460). By observing another patient, Broca confirmed that damage to the right hemisphere of the brain indicated a lesser effect on speech. Thus, Broca concluded that the left frontal lobe of the brain is responsible for language processing and essential to language performance. Throughout his career, other autopsies confirmed Broca's conclusion, and a section in the lower rear of the left frontal lobe was named Broca's area. Language production deficits following damage to this area of the brain are therefore often called ‘Broca’s (non-fluent) aphasia’.

In 1874, the German physiologist Karl Wernicke investigated an entirely different set of symptoms (Jackendoff, 1994, p. 146). In contrast to Broca’s patient, Wernicke’s patient had fluent speech but little comprehension of what was said to him. He produced well-formed fragments of speech that were apparently unrelated to the questions he was asked. After the death of Wernicke’s patient, the autopsy revealed that he had damage to the lower portion of the parietal lobe and left temporal lobe, below the most posterior portion of the lateral fissure. Thus, Wernicke concluded that a brain lesion in this area caused impairment of language comprehension. Later, it was noted that with more severe lesions, the phonemes are seemingly randomly selected, resulting in utterances which contain very few real words (Libben, 2011, p. 468). Therefore, based on autopsy studies in the late 19th century, for the first time in history, Broca and Wernicke discovered language areas in the human brain and made a very important argument in favour of the lateralisation of language functions. On the one hand, it was established that there is a functional distribution of language: damage to the left hemisphere of the brain in Broca’s area leads to disturbance of language performance, or Broca’s non-fluent aphasia. On the other hand, it was suggested that a lesion in the left hemisphere in Wernicke’s area was associated with comprehension deficits, or so-called Wernicke’s fluent aphasia. Thus, the clinical studies of the brain-language relationship gave a new perspective on language processing in the human brain. Furthermore, the famous clinical observations by Broca and Wernicke provided the first convincing neurobiological model of how language is organised in the brain. According to this model, Broca’s and Wernicke’s areas were acknowledged as the primary language areas, with Wernicke’s area being directly connected to the semantic representation of language in the brain (See Figure 1 below). Thus, this knowledge formed the basis of the classical model of language realisation in the human brain.

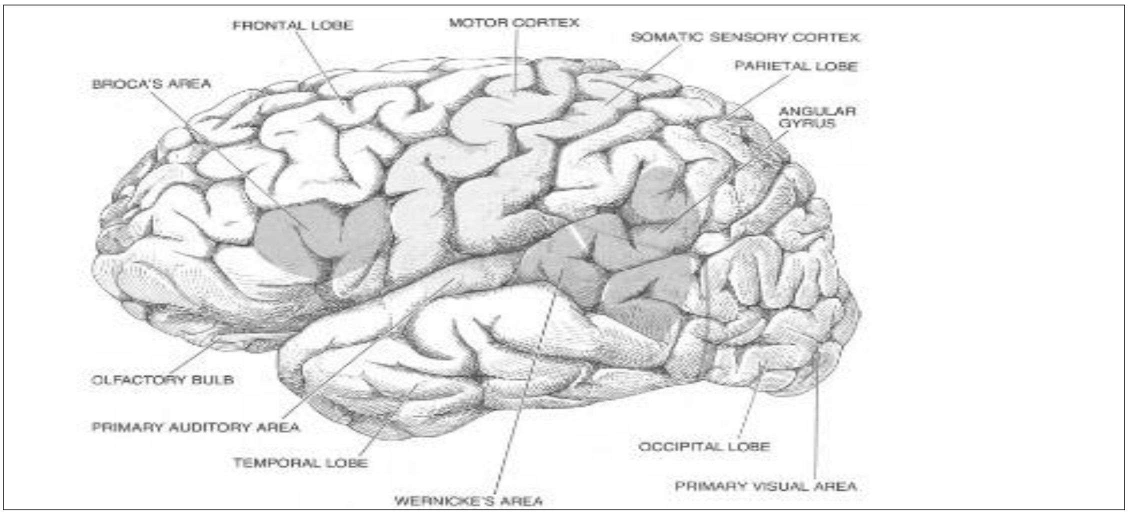

Figure 1. The left hemisphere of the human brain, illustrating the location of Broca's and Wernicke's areas related to language processing (adapted from Ingram, 2012, p. 11).

3. The Classical Model of Language

3.1 Evolution of the Classical Model

The classical model of language offers a simple and elegant way of understanding the brain-language relation. Furthermore, this model provides a clear explanation for the causes and the degree of language deficits that result from a brain lesion. And even though modern techniques have significantly expanded our knowledge of language processing, this model still has an enormous influence on linguistics, psychology and neuroscience. Thus, while acknowledging the huge influence of the traditional view on the understanding of language processing in the brain, this section discusses the issues and controversies surrounding the classical model, with a focus on semantics.

To begin, the classical model of language, which is also known as the "Broca-Wernicke-Lichtheim model" (Ingram, 2012, p. 40), the "Classical model," the "Broca-Wernicke-Lichtheim-Geschwind model," the "Wernicke-Lichtheim-Geschwind model," or the "Wernicke-Lichtheim model", refers to the neurological model of language based on a family of models with different historical and theoretical backgrounds (Tremblay & Dick, 2016, p. 61). This model views two language areas in the brain as essential. As mentioned above, the posterior region of the left frontal lobe is often referred to as Broca's area, with the posterior superior region of the left temporal lobe being referred to as Wernicke's area, in honour of the scientists who discovered them. Broca's area is linked to the capacity to produce speech, whilst Wernicke's area is linked to the comprehension of language. This is the way in which the classical model of language provides a simple and elegant account of the relationship between the brain and language.

In 1874, Karl Wernicke incorporated different aspects of language-specific deficits and proposed the first model of language behaviour based on brain anatomy (Tremblay & Dick, 2016, p. 62). Wernicke suggested a localisationist view of language neurology based on the distinction between particular language functions and their links to particular brain areas. A few years later, Lichtheim took advantage of Wernicke's model and added a very interesting thought. Lichtheim argued for a neuroanatomical model of language, and the existence of a neuroanatomical connection among the language areas in the brain, in contrast to the localisation model. It was clear that this proposal had merit, since the preservation or disconnection between direct and indirect anatomical pathways connecting the language areas seems crucial to whether language deficits are observed, instead of a preservation of language functions (Ingram, 2012, p. 53). Thus, the 'Wernicke-Lichtheim model' came to be very useful in the study of language pathology, but with time this model was abandoned. In the following years practically nothing of a crucial nature happened; many clinical studies continued to take place, but no major theoretical progress was observed in the study of language in the brain until 1965, when the American neurologist Norman Geschwind introduced and popularised the revised version of the classical model of language. Geschwind assumed that the connection between Broca's and Wernicke's areas is carried out by the *arcuate fasciculus*, or simply the bundle of axons between the language areas (Ingram, 2012, p. 54). Geschwind pointed out that large volumes of words may be carried through this system. In fact, it is this version of the classical model which has become widespread and is used for educational purposes to the present day. Thus, according to the classical model of language, semantics is solely served by Wernicke's area, and semantic processing is co-ordinated with syntactic processing via the *arcuate fasciculus*. However, the development of technological advances has made it possible for science to move beyond the first neurobiological model of language and consider a new way of understanding the neural mechanism underlying semantic processing. The next subsection addresses challenges to the classical model of language and reviews the significance of the results of modern studies in more detail.

3.2 Challenges from Semantics for the Classical Model

The aim of this subsection is to introduce the modern techniques which are widely applied in the study of language processing, and to provide a brief overview of related findings which suggest that semantic processing is not limited to Wernicke's area.

Although the classical model of language continues to play an important role in the understanding of the brain-language relation, modern advances in technology have challenged the simple localisation assumption of the traditional model. Much has been learned about the localisation of language, with non-invasive neuroimaging technologies that allow the study of language processing in the living brain in a more profound and dynamic way. Several types of neuroimaging techniques are particularly popular for studying where and how language processing occurs in the living brain. *Functional magnetic resonance imaging*, or fMRI, is a technique which provides information on which parts of the brain are involved in language processing by measuring brain activity via detecting the blood-flow changes through the entire brain; *electroencephalography* (EEG) is an imaging technique that records the slightest changes in the brain's electrical activities, by means of electrodes placed on the scalp; *magnetoencephalography* (MEG) measures magnetic fields produced within the brain (Libben, 2011, p. 463). *Computed tomography* (CT) scanning builds the detailed images of the brain using X-ray beams and computer technology (Libben, 2011, p. 461).

A rather different technique involves non-invasive non-damaging interference with the activity of specific neuron clusters. The mechanism of *repetitive transcranial magnetic stimulation* (rTMS) is similar to direct electrical stimulation, except that it uses magnetic impulses to stimulate nerve cells via a 'coil' (Luan, Williams, Nikolic, & Constandinou, 2014). In this case, the stimulation of particular areas in the brain is associated with possible changes in the participants' behaviour. rTMS therefore allows for a flexible application of the classical autopsy method, but with living patients: disruption of a particular area in the brain is linked to changes in behaviour.

Finally, psycholinguistics provides a range of behavioural techniques for investigating the processing load on the brain. In fact, due to modern techniques that allow the study of language in real time, understanding of language processing has been greatly increased. For example, it was found that when a person speaks, blood-flow increases in the frontal lobe of the left hemisphere, and when a person reads, blood-flow increases in the occipital cortex and other regions of the left hemisphere; new technologies have also provided compelling evidence that second-language processing involves wider areas of the brain than first-language processing requires (Libben, 2011, p. 463). Furthermore, analysis of the living brain as it performs cognitive functions has revealed the possibility that semantic processing is not limited to Wernicke’s area, as the traditional model implies. This observation is supported by the range of brain and language studies that claim that all language deficits are not necessarily directly related to specific language areas of the brain (Ghaleb, 2017).

Modern findings have also provided evidence that the causes of aphasia are not as simple and consistent as the classical model suggests. For example, it has been found that not every brain lesion predicts retention or impairment of language functions. Furthermore, damage to Wernicke’s area does not provide uniform results. First, according to clinical studies, females are less likely to suffer from aphasia after a certain type of brain damage than males are (Tortora & Nielsen, 2014, pp. 585-631). Second, in some cases, patients suffering from Wernicke’s aphasia may also show deficits in language production (Ghaleb, 2017, p. 1181). Third, patients with cortical degeneration outside Wernicke’s area have shown impairment of semantic memory. For example, patients with cortical degeneration may remember the name of an object but they may also lose all knowledge concerning the object’s function(s) (Binder, 2017). In fact, the results of these and similar findings provide evidence against the traditional view of the neurological pattern of language processing, and suggest the importance of other regions of the brain in language comprehension.

A growing body of research indeed shows that unexpected areas of the cerebral cortex are implicated in semantic processing. For example, recent studies have provided evidence for the involvement of subcortical regions of the brain in semantic processing, in addition to Wernicke’s area (Ghaleb, 2017, p. 1180). It appears that the thalamus, a paired oval structure of grey matter masses which are located within both hemispheres, is engaged in meaning processing (Ghaleb, 2017, p. 1180; Tortora & Nielsen, 2014, pp. 585-631) (see Figure 2 below). Even though the particular role of the thalamus in the processing of word meaning is still unclear, these findings have led to a debate on other issues regarding the ‘lateralisation’ and ‘hemispheric dominance’ of language functions (Ghaleb, 2017, p. 1180). In the studies of semantic processing, the motor cortex has also received great attention.

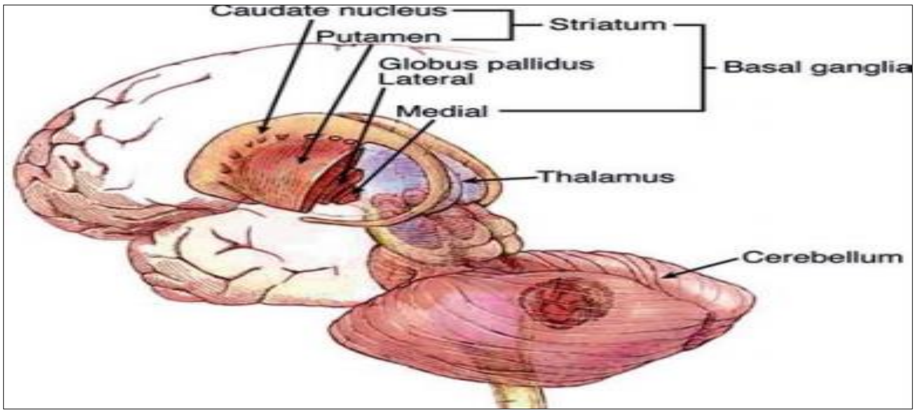

Figure 2. Image of the subcortical structures of the brain from inside, including the thalamus (adapted from Ghaleb, 2017, p. 1180).

Recent studies show that one of the most important non-core language areas of the brain to be implicated in semantic processing is the motor cortex. Decades earlier, the language deficits exhibited by people with various types of aphasia pointed to a modular organisation of language in the brain. However, contemporary findings propose a new model of language, a multimodal brain system which links semantic processing to additional cortical regions, such as the motor, visual and auditory cortices. While many studies agree upon the multimodal or modality-specific brain system concept, some proponents of this new model disagree in theory as to whether the motor and sensory cortices of the brain functionally contribute to semantic processing (Vukovic et al., 2017, p. 222).

The supporters of the 'amodal' or 'multi-modal' approach attempt to reconcile the modern understanding of the semantic mechanism with notions of the classical model of language behaviour, arguing that activities outside the perisylvian areas are not necessarily related to the functional processing of meaning. Supporters of the 'amodal' understanding claim that the activities observed outside of the language areas purely reflect neural network correlations and suggest that such neural activities do not essentially contribute to the functional processing of word meanings, since the specific activities within those regions may depend on other factors (Vukovic et al., 2017; Dreyer & Pulvermüller, 2018). Thus, supporters of the 'amodal' understanding assert that semantic processing is presented only in the classical cortical area and nowhere else.

The supporters of category-specific or modality-preferential theories of the brain system of semantic processing consider an ‘amodal’ approach to be limited and state that it may even be erroneous. They argue that language comprehension activates additional cortical areas related to the bodily experience, highlighting the mechanism of semantic category processing. Various contemporary studies support this model by illustrating how the brain responds differently to action- and object-related words. According to these findings, the object-related words mostly activate the visual, olfactory and gustatory regions of the brain, which are bound to the sensory areas of the cerebral cortex; whereas action-related verbs, as well as body-movements words, activate the motor areas of the brain (Tomasello, Garagnani, Wennekers & Pulvermüller, 2017, p. 112). For example, fMRI evidence indicates that action-related words, such as *run*, *kiss*, or *push* are associated with increased blood-flow to the areas of motor cortex which directly control the movement of our legs, mouth or hands (Tomasello, Garagnani, Wennekers & Pulvermüller, 2017, p. 112; Vukovic et al., 2017, p. 223). Furthermore, results of studies using EEG/MEG techniques illustrate that activity in the motor areas increases very fast even during second-language processing (Vukovic et al., 2017, p. 223). Later neurolinguistic studies have fixed on the importance of the motor areas of the brain in semantic processing, by indicating neurological activity across motor areas of the brain even when participants ignore demonstrated symbols of semantic meaning (Dreyer & Pulvermüller, 2018, p. 54). Thus, the results of various studies have confirmed the involvement of the motor cortex in semantic processing and have argued for the neurological reflex of many motor areas during action-related word comprehension. However, this evidence has caused many discussions and much controversy regarding abstract semantics. The followers of the traditional view of language comprehension assume that the brain processes language by manipulation of semantic symbols (a kind of mentalese or language of thought), on analogy with how computers manipulate symbol representations (Galetzka, 2017). The proponents of an embodiment approach to language comprehension emphasise that abstract semantics is grounded in physical experiences and relies on the neurological mechanism of the sensory and motor areas, by use of the example of action-related concrete words (Dreyer & Pulvermüller, 2018, pp. 53-55).

The theoretical explanation for semantic grounding comes from an embodiment theory developed within cognitive psychology, which assumes that human cognition is formed by body experience. Cognitive linguistics has adopted embodiment theory in order to provide an account for the representation of language competence in speakers. This refers to a way of explaining how linguistic categories are constructed out of basic schemas grounded in physical experience (Lakoff & Johnson 1980, Johnson 1987), which assumes that categories emerge from bodily experience rather than being innately specified. This approach makes it possible to explain more complex concepts, which are used in the language. According to the theory of embodiment of language, abstract concepts are built on concrete meaning, since abstract concepts are formed in the human mind due to embodied experience. Although the relation between action words and physical experience is more direct and obvious, ultimately all meanings are built up out of the way that we process and understand physical embodied experiences. Thus, embodied experience is reflected in the semantic structure; and vice versa, the semantic structure reflects embodied experience. Thus, in order to process the meaning of abstract words, it is also necessary to activate the neurological structures of the motor cortex to be able to extract the necessary additional information. For instance, in the metaphor 'he cooked up a story,' the abstract creative process is understood in the context of physical action, which links the abstract concept to the bodily experience and thus to the motor areas of the cerebral cortex. In fact, recent modern studies of the living brain support the embodiment approach to language comprehension by showing that damage to motor areas can result in comprehension difficulties for abstract words (Galetzka, 2017).

To summarise, this section permits the conclusion that the embodiment theory of cognition illuminates not only the fundamental aspects of human cognition, but also predicts the significant role of the motor cortex in semantic processing. What is also of importance is the fact that modern findings have provided support for the embodiment theory by offering compelling evidence for how and where action-related and abstract words are represented and processed in the human brain. Findings which support the activation of motor areas in semantic processing, therefore, challenge the classical model on two levels. First, they show that semantic processing is not limited to Wernicke's area but implicates areas which are apparently independent of specialised semantic processing. Second, they integrate those findings of motor activation into a broader theory of the relationship between neuroanatomy and cognitive functions, in which linguistic processing is not separated as a specialised function from areas handling bodily and sensory experience but rather is integrated with those systems at a deep level. Strong support for both these challenges could be drawn from the rTMS (Vukovic et al., 2017) and fMRI (Dreyer & Pulvermüller, 2018) studies which have tested the functional role of the motor cortex in language comprehension.

4. Outside the ‘Core System’: Sensory and Motor Areas

In the previous sections it has been shown that the development of modern techniques exposed the oversimplicity of the classical model. Contemporary studies reveal that semantic neurological structure is distributed within the brain in a wider and more interconnected way than indicated by the classical model. Furthermore, a new outlook on language processing suggests that in order to process language comprehension, the brain needs to involve the motor areas of the brain in addition to Wernicke’s area. Importantly, the significant role of the motor cortex in semantic processing was predicted by the embodiment theory of meaning, which has grounded semantics in the essential mechanism of the bodily experience.

In order to support the argument in favour of a functional role for the motor cortex in language comprehension, this section reviews two crucial studies. Section 4.1 reviews an rTMS study (Vukovic et al., 2017) which establishes that disruption of motor function will also disrupt the semantic processing of action words, i.e. that the motor areas contribution is not just an optional correlate to processing, since it is in fact presented as a necessary part of semantic processing of action word meanings. This addresses the first point made in this section, that motor areas of the brain are functionally involved in semantic processing. Section 4.2 reviews and reports on an fMRI study (Dreyer & Pulvermüller, 2018) which establishes that motor areas of the brain are involved in the processing of subcategories of concrete and abstract words. This discovery addresses the second point of this thesis, namely that motor areas of the brain contribute to the comprehension of abstract and not just concrete words.

4.1 The Role of the Motor Cortex in Language Comprehension

In order to highlight the functional involvement of the motor cortex in language comprehension, this section presents the study of Vukovic et al. (2017), in which online *repetitive transcranial magnetic stimulation* (rTMS) was employed. Vukovic and his colleagues assessed language processing by the primary motor cortex and concluded, on the one hand, that disruption of the left hemisphere motor functions results in a disruption of semantic processing of action-related words; and on the other hand, that the motor cortex of the brain is directly involved in semantic processing rather than as a side effect of language comprehension.

Examining previous studies, Vukovic et al. (2017) identified missing evidence regarding the functional role of the motor areas, and suggested taking a new approach from a different angle; in particular, a study of the effect of disturbance within the motor areas upon the understanding of action words. The experiment was designed to examine the causal role of motor areas of the brain in a semantic judgement task and a lexical decision task. The group of researchers directly measured behavioural outcomes, or reaction times, during linguistic tasks, to contrast the performance in the concreteness judgement task with the lexical decision task. In the experiment, *repetitive transcranial magnetic stimulation* (rTMS) was used to disturb the functions of the left and right motor hand areas, where the right hemisphere was used as a control site. Based on the results from previous studies, the group of researchers predicted zero reaction in time for the right control area and expected to see the stronger effects in semantic judgement tasks, rather than in lexical tasks.

Volunteer participants in the study included twenty-eight healthy right-handed native speakers of Russian. Ten of them were male and eighteen were female. In the group, no one had a history of neurological or language disorders, and everyone had normal or correct-to-normal vision. The average age was approximately twenty-three years old. During the experiment, the participants were seated in comfortable armchairs with their hands fixed in the rest position in front of a screen and were instructed to push the button when they recognised the category, to which a word belonged, flash up on the screen. The response, according to the instructions given, could be made using the right or the left hand. However, in order to avoid a downstream reaction, the response hand was located ipsilaterally to the stimulated cortex.

During the study, the left and right cerebral cortex hand areas were stimulated by rTMS. The stimulation time for each word was present for 200 ms followed by 50-ms gaps in between. The experiment investigated the word processing in two visual timed tasks: lexical decision vs. semantic judgements. This helped to investigate the contextual differences in processing (Vukovic et al., 2017). According to the requirements of the study, each participant was asked to complete both tasks, the lexical decision and the semantic judgement tasks, as quickly as they could.

The lexical decision task stimuli consisted of fifty real Russian hand action words, such as *рисуешь* ‘draw’ and *пишешь* ‘write’, adapted from the Russian Internet Corpus and Russian National Corpus. Other sets consisted of fifty pseudo-words, which follow the phonotactics and orthography rules of Russian language grammar, for instance: *шмакишь* and *белдешь*. In each session, the experimental group was asked to respond to the real or pseudo words by pressing one of two response buttons as quickly as they could. For those who responded outside the required time limit, an illuminated text appeared on the screen saying they were ‘Too Slow’.

In the semantic judgement task, the participants followed the same rules as they were given in the lexical decision task, the exception being that there was only a single set of words. In this task the participants were presented with concrete action-related words, and abstract cognitive words unrelated to body movements, such as *think*, *infer*, and *decide*, which in turn require a more comprehensive approach to the processing of the word meaning. The aim of this task was to indicate which types of word meaning are supported by the motor cortex.

According to the first results, all participants completed both tasks with fewer errors in the lexical decision task, where the error rate was only 3.3%, while the rate of errors was 9.1% in the concrete judgement tasks. However, further analysis showed a more meaningful difference between the results of the lexical decision and semantic judgement tasks. For instance, by measuring reaction time in both tasks, the researchers recognised two significant factors affecting the response to the action-related words.

First, it was observed that disruption of the left motor hand area disrupts the processing of action words compared to the right-hemisphere, and this supports the long-established claims regarding left-hemisphere dominance with language processing. Second, it was observed that disruption of the left motor cortex neural activity only slowed down the reaction time in semantic judgement tasks, in contrast to faster reactions in the lexical decision task. Thus, if disruption of the right motor hand area did not show any differences in response in both tasks and all types of words, then the interruption of work of the left hemisphere hand area lead to a significant difference in response time to action-related words in the semantic judgement task. According to the paper (Vukovic et al., 2017), 'disruption of the motor cortex hand representation during word processing led to hemisphere, task, and meaning specific changes in the speed of behavioural response' (p. 226).

To summarise, with the investigation of word processing in the left and right hemispheres of the motor areas, the study by Vukovic et al. (2017) provides evidence for the functional role of the motor cortex in semantic processing for action-related words. The results indicate that suppression of the left hemisphere hand motor areas slows down the semantic processing of hand action-related words after rTMS stimulation. In this case, it seems evident that in order to get access to the meaning of the words, our brains have to 're-experience' the real-life action using the motor cortex. This result provides strong evidence that motor areas of the brain functionally support language comprehension and do not simply activate as a side-effect of other activity. However, Vukovic and his colleagues emphasise that they do not claim that motor areas of the brain play an exclusive role in language comprehension, since the dysfunction of the motor cortex does not always lead to difficulties in understanding of the meaning (Vukovic et al., 2017, p. 227). However, it is fair to say that their findings largely support the theoretical theory of language embodiment for concrete words, while leaving scope for future studies regarding the processing of abstract words.

4.2 Abstract Emotional and Non-Emotional Nouns

In order to provide full evidence for the functional contribution of the motor cortex in semantic processing, this subsection presents the Dreyer & Pulvermüller (2018) study which employed advanced functional magnetic resonance imaging (fMRI) techniques. This subsection implies that the motor areas of the brain are not only involved in processing concrete action-related words, but also that the engagement of motor areas for processing of abstract semantics is not merely a sympathetic correlative response; this implication is more indirect than for the Vukovic et al. (2017) study. The compelling argument for this statement comes from evidence of how subcategories of abstract and concrete nouns differently affect the motor areas of the brain. Ultimately, the processing of subcategories of abstract semantics supports the embodiment approach to understanding the mechanism of language comprehension, and confirms that the neurology of semantic processing is much more complex than the classical model suggests.

The authors of the project chose three groups of words for a passive reading experimental paradigm. The first group included so-called *disembodied* abstract nouns, such as *logic,* or *thought.* From the researchers' point of view, these are the perfect words for the study of semantic processing, since they do not bear any emotional information. The second group presented abstract emotional words, such as *disgust,* as a contrast to non-emotional nouns. In addition to abstract categories of words, action-related nouns were also presented. This group included *food* and *tool* categories of words, since previous studies show that these types of words differently affect face and hand/arm motor areas of the brain (Dreyer & Pulvermüller, 2018, p. 59). Therefore, the authors of this study expected to distinguish activities in the motor and sensory areas of the brain, in addition to the key area of language processing, not only during the reading of the subtypes of concrete action-related words, but also in the semantic processing of the subcategories of abstract nouns. Based on the statement that linguistic information is more important for abstract words than for concrete words, and on the assumption that people tend to express their emotions by bodily movements which might be reflected in the semantic processing of abstract words, it was predicted that abstract non-emotional nouns would activate face motor areas more strongly than the hand motor cortex; while abstract emotional words would activate equally both face and hand areas. In contrast to this prediction, the traditional view on language behaviour denies the embodiment approach and any such connection between semantics and the motor cortex. Thus, in order to reconcile the embodiment theory on cognition with the understanding of the mechanism of language comprehension, the aim of this study was to provide evidence for the functional role of modality-preferential sensorimotor areas in semantic processing, by showing that the causal role of the motor cortex is not limited only to concrete words, but also extends to abstract words to some degree. Ultimately, these results confirm that embodiment theory is crucial to the understanding of how the brain comprehends meaning.

Twenty-eight native speakers of German participated in this study, sixteen of whom were female. All participants were right-handed, healthy and had normal or correct-to-normal vision and no recorded neurological or psychiatric diseases. The average age of the participants was 23.7 years old. During the research, brain activity was measured by fMRI.

To determine the connection between the meaning of words and the motor areas of the brain, 160 nouns of interest were used. In addition, 120 hashmark strings were applied to a task as visual baselines. The researchers also used 320 filler words on purpose to hide the aim of the study and to increase the perception of word meaning variability. All nouns of interest included 40 stimuli from four semantic categories. The first two categories presented concrete objects, such as tools and food items, for instance, *sage/saw,* and *apfel/apple*. The third category presented abstract emotional words, such as *liebe/love*, and the fourth contained abstract non-emotional nouns, such as *logik/logic*. Within all groups of words, the nouns of interest were characterised by lexical, sub-lexical, and psycholinguistic characteristics. The following factors were controlled for: word length; the number of syllables; normalised lemma; character; character bigram; character trigram frequency; and also word-initial character; word-initial bigram; and word-initial frequency (Dreyer & Pulvermüller, 2018, p. 60). No significant psycholinguistic differences were found between the semantic groups. In the semantic tasks, words were matched for relatedness to emotions and mental processes, and also with action perception, such as *hand/arm, face/mouth,* or *leg/foot* actions, to visual, olfactory, gustatory, and haptic/tactile. Nouns were compared on the scale from ‘no relation’ to ‘strong relation’. Regarding the scale of concreteness, height concreteness and height abstract groups were formed. It should be noted that in the study low semantic variance words were used to avoid a possible ambiguity of word meanings presented out of context.

The reading task was performed with participants lying in the fMRI machine. During the test, participants silently read words with a short interval, in order to avoid eye movement or other types of activity, which can affect data. Each fixation cross appeared for a short time, on a black screen with printed white letters. The experiment was divided into four blocks. In addition, a visual hint which consisted of only two letters was given in this case to avoid visual processing. As a result, in the behavioural task, the analysis indicated acceptable attention and processing of the listed words was the norm.

In order to measure the involvement of motor areas of the brain in semantic processing, a localised motor task was performed. To avoid any specific activity in motor areas towards semantics, the participants were given restricted access to information. Still lying in the fMRI machine, participants were invited to repeat the movements of different parts of their bodies, as they were shown on the screen inside the scanner. In order to create a semantic atlas of brain activity, the participants of the experiment moved their lips, tongue, the fingers of the right hand, and grinned or frowned, using only the muscles related to the movement of these areas. The aim of this test was to identify the existence of differences between semantic classes in general semantic and motor areas.

The results show that the category of *food* words indicated strong relatedness to both categories of *hand/arm* and *face/mouth* motor areas, the dorsal and ventral motor cortex, while the *tool* category of words showed relatedness to the *hand/arm* motor areas of the brain. Furthermore, the semantic processing of the words was indicated in the motor areas of the brain between the subtypes of the abstract words. Interestingly, both concrete and abstract classes showed stronger activity related to the face motor areas rather than the hand area. However, the abstract emotional nouns demonstrated a more pronounced connection to motor areas, as opposed to mental or non-emotional words. Unexpectedly for the authors of the study, the abstract emotional words caused stronger activity to the face motor areas rather than abstract mental words, while relatedness to the hand motor areas was equal for both subcategories of words. However, the authors point out that in general, the relatedness was very weak even for the abstract emotional words. Overall, it might be noted that the semantic tests indicated the relatedness characteristics for all word categories, and the neuroimaging results provided evidence for activity in sensory and motor systems, in addition to classical language areas. It is also important that the results provided by this study support the conclusions of previously reported studies in passive word reading (Dreyer & Pulvermüller, 2018, p. 59) (see Figure 3 below).

To summarise, the Dreyer and Pulvermüller (2018) study provides the first brain imaging evidence for the direct semantic relationship between subcategories of abstract words and motor areas. The main results of this study indicate that motor areas of the brain are differently affected by different types of abstract and concrete nouns (Dreyer & Pulvermüller, 2018, p. 56). To summarise, the researchers provide evidence for neural activity in the motor areas of the brain in addition to Wernicke's area, demonstrated in a passive reading task without any movement. The motor localised task for the specific somatotopic dissociations indicated significant motor activity in the regions controlling movements related to the *face/mouth* and *hand/arm* areas of the motor cortex. When *tool* word category triggers were used, most activity happened in the hand areas of the precentral/premotor areas, and the *food* category of words were more related to the face areas of the motor cortex. Furthermore, the passive reading of the action-affording object nouns provides evidence for the semantic processing of abstract emotional and non-emotional words in the motor cortex. According to the results of the study, the abstract non-emotional words, or mental nouns, such as *logic* or *thoughts*, more strongly activate the face motor areas than the hands areas, while abstract emotional words, such as *love* or *hate* equally activated the face and hands motor areas of the cerebral cortex. Thus, these results confirm the motor areas' contribution to semantic processing by showing how the passive reading of subcategories of abstract words activates the motor regions of the brain differently.

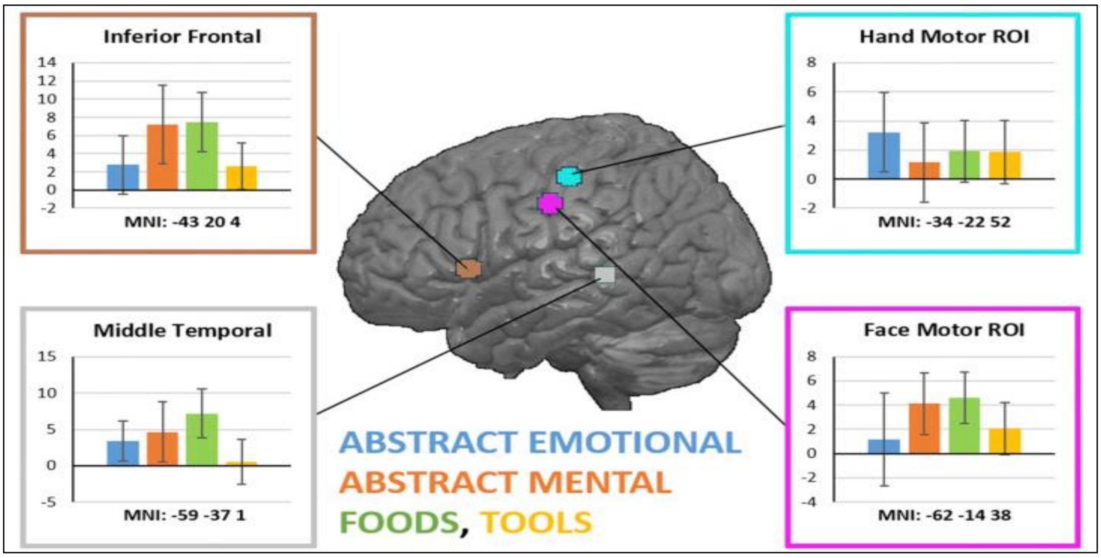

Figure 3. Region activation by semantic class (adapted from Dreyer & Pulvermüller, 2018, p. 61).

5. Conclusion

This thesis argues in favour of the claim that language comprehension is rooted in the motor cortex, in addition to the main language areas, since cognition is grounded in the neurological system of perception and body movements. Until recently, knowledge regarding semantic processing in the brain was largely informed by the classical model of language, which posited a direct connection between areas of the brain and different aspects of language function based on the study of damaged brains post-mortem. According to these findings, the language comprehension process is served by Wernicke's area. Subsequently, the understanding of the neural basis of language was profoundly changed by the introduction of techniques allowing the study of language in the living brain. The results of new findings have identified that the neurobiology of language is much more complex than the traditional model suggests. While many studies support a new outlook on the general neurology of language, some disagree on the issue concerning the relationship between the physical processing mechanisms and semantic processing. Thus, two crucial studies are presented here, which provide strong evidence in favour of the functional contribution of motor areas of the brain in language comprehension by showing how action and abstract words are linked to the motor cortex.

Vukovic and his colleagues (2017) tested the functional involvement of the primary motor cortex in language comprehension. The researchers reported that disruption of the primary motor cortex by rTMS slows down the response reaction to action-related words. This result led to the conclusion that the involvement of the motor cortex in language comprehension is a function in semantic processing rather than a reflexive correlation. However, the research stresses that the extreme claims of some studies are not supported, notably that motor areas alone carry out a causal role in semantic processing, since lesions in motor areas do not always lead to difficulties in language processing.

The Dreyer and Pulvermüller (2018) study, on the other hand, provides the first functional brain imaging evidence showing how high-level cognition of language is directly connected to the motor areas of the brain. The main result of this study is that the motor areas of the brain are shown to be differently affected by different subtypes of concrete and abstract nouns (Dreyer & Pulvermüller, 2018, p. 67). This result certainly suggests that motor areas of the brain functionally contribute to language comprehension. However, the authors of this project also emphasise that their study does not imply that activity in the motor areas is exclusively the result of semantic processing, since the involvement of motor areas may be also related to other functions of language processing (Dreyer & Pulvermüller, 2018, p. 62).

To conclude, the discovered findings provide compelling evidence that motor areas of the cerebral cortex, in addition to the traditional language area of the brain, functionally contribute to the comprehension of word meaning. The current results coincide with the embodiment theory of cognition, which predicts the importance of the neurological system of the motor cortex in language comprehension. These findings suggest that the gap between language and body experience is not as large as the classical model implies. Still, the studies reviewed in this thesis also highlight that the extent and exact nature of the motor cortex contribution remains unclear. The current findings can be linked to potential new knowledge of language processing and may perhaps contribute to the development of fundamentally new types of therapy for people with aphasia and different types of language pathology.

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