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Neural basis of lexical-semantic processing and integration of symbolic gestures with words

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PREFACE

Language is a unique possession of humans. Through speaking we communicate our needs, thoughts, emotions, experiences, intentions. When written language appeared a millions of years ago, human communication became free of spatial and temporal constraints. We can read about experiences of other people, learn notions, read stories, share knowledge; we can communicate with other people even if they are very distant from us. It is not pretentious to say that language was the revolution of social human's life.

Maybe for this reason, a lot of researchers in the world have been interested in language and continue trying to discover more about it. Where language come from? How was the human communication before language? Some theories tried to explain language phylogenetic development examining the link between language and manual gestures. The current presence of manual gesture in every culture in the world suggested to some authors that manual communication could be important also for our ancestors and maybe could have been the precursor of the oral communication as we know it now. Furthermore, the present-day use of gestures also in concomitance of language suggests a special link between the two modalities that can't be fortuitous.

Another problem strictly related to language is the representation of language meanings, or more generally, the representation of concepts and semantics in our brain. If we think about the manual communication, we inevitably have to think about a direct connection of meaning's expression respect to the possible actions toward the physical world. This equation is not always valid for language, when abstract concepts could express more complex meanings and relations, or not perceivable things without a clear match with the concrete world. It is possible that language concepts are directly built from sensorial and motor experience and for this reason it is fundamental to demonstrate in what form concepts are represented in our brain and to what extent they could be modality specific (i.e. related to our physical experience) or symbols not related to a modal form.

To analyze the relations between word and gestures as well as that of semantics with actions could shed light to neural process and systems involved in language development; moreover, discovering the neural basis of communication could tell us more about the systems that are probably involved in social cognition.

With this work, I will present some recent results that give strength to the theory of the integration between gestures and words and clarify some mechanisms about the processing of abstract/symbolic words. Prior to present these results, is necessary to introduce the background of theories about semantic cognition and about the relation between gesture and words, as well as the huge evidence of research that has faced this problem.

The implication of the advancement of research in this field could not only give knowledge about the origin and nature of language and neural basis of semantic processing, but could also be useful to develop new rehabilitation programs for populations with language disorders, in adults with brain lesions like aphasic patients, or in children with developmental disorders. The potential link with sensorimotor systems could become a powerful tool to enhance communication in populations with damaged language system, either at the production or the comprehension level.

INTRODUCTION

Chapter 1 – Introduction to embodied cognition

1.1 Embodied cognition: a brief review of theories and evidences

Semantic concepts constitute a main part of human cognition. They are the basis for object recognition, action planning, language and thought, because they constitute the meaning of sensorial world and abstract ideas (Humphreys et al., 1988; Levelt et al., 1999). Concepts are representations derived from our sensory and motor experiences in the environments, they can be linked each other (i.e., the concept of cat is linked to the concept of animal), and can refer not only to concrete elements but also to abstract ideas or elements that do not belong to reality. Finally, they are not bound in time or space, since we can communicate our experiences before or after we have lived them, and think about concepts without the necessary presence of the things we are speaking about.

These features suggested to cognitive scientists that semantic memory was a container of symbols, as pure abstract representations, derived from a transformation of the sensorimotor experience (Pylyshyn, 1984). In this vision, semantic and conceptual processes can be attributed to a dedicated hub called "symbolic semantic system" that handles semantic information about concepts (Collins and Loftus, 1975; Ellis et al., 1988). These classic cognitive theories focused on the structure of semantics and relations between concepts without taking in account the kind of content that underlines meaning. In fact, the nature of semantic concepts is still at the centre of a debate. In other words, it is not still clear how and at what degree concepts are grounded in our senses.

The tight link between sensory world and symbols could be explicated through the process of *simulation*. Simulation does not implicate a transformation of the concrete experience in a symbol but activates semantic concepts through a re-enacting of the experience. In this sense, the content of semantics is a sensorial and motor content: these claims are at the centre of the ***embodied*** **theory of cognition**.

Meteyard et al. (2012) reviewed the main developed theories about the nature of concepts (Fig. 1), sorting them from complete disembodied theories to strong embodied theories. Disembodied theories consider the nature of semantic content as completely amodal, so not strictly dependent of sensory modality through which the concept could be experienced. On the other side, strong embodied theories consider concepts as modality-dependent and they claimed that all concepts were built and understood on the basis of sensorimotor experience (see Gallese, 2008; Gallese and Lakoff, 2005).

As secondary issue, authors (Meteyard et al., 2012) considered the relation and the way of interaction between concepts and motor systems. Theories take place along a continuum that starts from a complete independence from sensorimotor systems to a complete dependence. These kinds of relations obviously characterize the semantic activation process and the neural systems involved in concepts comprehension and manipulation.

For example, Mahon and Caramazza (2008) proposed that all concepts are represented at an “amodal” level, not primarily constituted by sensory and motor information. In this way, interaction with motor systems is a consequence of the spreading activation from amodal representation to modality-specific information related to the concepts.

Label	Unembodied	Secondary embodiment	Weak embodiment	Strong embodiment
Sematic content	Symbolic / Amodal	Amodal	Cross-modal integration / Supramodal	Analogue / Multimodal
Neural architecture	Semantic region(s) have no temporal or spatial overlap with sensory and motor areas	Region for amodal semantic content plus modality specific regions which code experiential attributes	Distributed network of areas which code integrated modal information, proximal to primary sensory and motor regions	Distributed network of areas within primary sensory and motor systems
Relationship to sensory-motor systems	Complete independence	Independent but associated	Partial dependence	Complete dependence
Explanation of interactions	Indirect activation	Secondary activation	Mediation	Modulation
Theories	Collins & Loftus (1975) Landauer & Dumais (1997) Levelt (1989)	Mahon & Caramazza (2008) Patterson et al (2007) Quillian (1968) Rogers et al (2004)	Barslou (1999) Farah & McClelland (1991) Pulvermuller (1999) Simmons & Barsalou (2003) Tyler & Moss (2001) Vigliocco et al (2004)	Gallese & Lakoff (2005) Glenberg & Kaschak (2003) Zwaan (2004)

Figure 1 - *A continuum of embodiment. Theories are divided into four broad groups. From left to right: (1) Unembodied, in which semantic information is symbolic/amodal, with complete independence from modal content and no neuroanatomical overlap with sensory–motor systems. (2) Secondary embodiment, in which semantic content is amodal, but associated to (separate) brain regions that represent modal information. (3) Weak embodiment, in which integrated modal information that is represented proximal to sensory and motor regions forms the basis of semantic content. (4) Strong embodiment, in which primary sensory and motor regions represent semantic content in a distributed network via simulation. Adapted from Meteyard et al., (2012).*

Neural basis associated with amodal representations are currently evidenced in areas of anterior temporal lobe (Hodges et al., 1992; Patterson et al., 2007a; Pobric et al., 2010). Sensorimotor activation in this case would be only accessory and subordinate to the initial instantiation of the amodal information. Modal activation enriches the concept with experiential attributes but is not the essence of it. At the opposite, Gallese and Lakoff (2005) proposed that semantics is essentially constituted by sensorimotor (or "modal") representations and the same systems take part as protagonists in the semantic processing. These brain areas would be directly modulated by semantic processing, since they are used to represent semantic content through the simulation process. Therefore, in this view, the same neural substrates are used for perceiving/doing, imagining and for linguistic understanding.

Another classification made by Kiefer and Pulvermüller (2012) sorted conceptual representation theories on the basis of four dimensions concerning semantics: 1) the amodal or modality-specific representation; 2) the local vs. distributed network; 3) the innate vs. experience dependent representation, and 5) the flexibility vs. stability of the concept.

Amodal theories assume either localist (Collins and Loftus, 1975; Collins and Quillian, 1969) or distributed view of concepts representation (Caramazza et al., 1990; McClelland and Rogers, 2003; Rogers et al., 2004). Localist representations assume that each concept is stored as a node, on the basis of the experience; Semantic related nodes are connected each other and form together propositional knowledge (e.g., a birds can fly) but each node constitutes an independent and stable concept. Stable concepts representations are also part of the theory of domain-specific representations (Caramazza and Mahon, 2003) that in opposition to the idea of a single unique semantic system propose the existence of different innate categorical subsystems, selected by evolution, where concepts are represented on the basis of visual and functional features (e.g., animate vs. inanimate subsystems, see Warrington and Shallice, 1984).

In contrast, distributed models (e.g., feature list or PDP models, Caramazza et al., 1990; McClelland and Rogers, 2003; Rogers et al., 2004), propose an organization of semantic memory like a distributed net of multiple representational units that represent different features of a concept, which different contribution can vary across different contexts. In this case, the concept is represented in a flexible way that depends of different activations among the processing "semantic units". Modality specific theories (Embodied theories, Barsalou, 2003; Martin, 2007; Pulvermüller and Fadiga, 2010; Gallese and Lakoff, 2005) preserve the same distributed and flexible features; access to concepts involves a partial reinstatement of brain activity during experiences, through the words are typically used to speak about them, representing concepts in a distributed fashion at a functional level (Kiefer and Pulvermüller, 2012). This approach however, is centred on the grounding-based acquisition of concepts and suggests that the activated cortical areas used to understanding meanings should differ, for example, on the basis of the functional and visual characterization of the objects (e.g. concept of "tool" could be more active in the parietal-frontal circuits than animals, see Pulvermüller, 2013). Differences between feature list/PDP models and embodied cognition appear, as we have seen before, when we consider which neural structures are responsible of semantic processing. In addition, a part of the problem is the endorsement of a direct matching between sensorial experience and concept (Humphreys et al., 1999; Kiefer, 2001; McRae et al., 1997; Pulvermüller, 1999), or a necessity of an indirect representation between sensorimotor experience and concept (i.e., a lexical representation; Levelt et al., 1999; Vigliocco et al., 2004).

Understanding the specific features of the different approaches and comparing them with scientific evidence is necessary to guide empirical research to give considerations in favour of one rather than another theory.

Concerning the first dimension (modal vs. amodal) discussed in Kiefer and Pulvermuller's review (2012), many studies in recent years provided a great number of evidence in support of the embodied theory (Barsalou, 2003; Kiefer and Pulvermüller, 2012; Kiefer and Spitzer, 2000; Pulvermüller, 2005; Gallese and Lakoff, 2005) using the methods of cognitive neuroscience in healthy volunteers, but also in brain-damaged patients. In particular, neurophysiogical studies gave evidence on involvement of modality-specific sensory areas during processing of language and concepts in different tasks (for an overview, see Kemmerer and Gonzalez-Castillo, 2010; Martin, 2007; Pulvermüller and Fadiga, 2010) and different modalities, from auditory (Kiefer et al., 2008) to visual (Chao et al., 1999; Kiefer, 2005; Pulvermüller and Hauk, 2006; Sim and Kiefer, 2005), to olfactory (Gonzalez et al., 2006, Simmons et al., 2005). Activation of motor system was evidenced during language processing, in particular during action-related words processing (Boulenger et al., 2009; Dalla Volta et al., 2014; Hauk et al., 2004; Hauk and Pulvermüller, 2004; Innocenti et al., 2013; Pulvermüller et al., 2001).

Examining the second dimension (local vs. distributed representation of concepts), poor evidence was provided for the existence of a local distribution, despite specific cell activity was measured in response to particular stimuli (for a review see Bowers, 2009). In contrast, evidence from clinical studies as from neurodegenerative pathologies like semantic dementia or Alzheimer's disease suggested a loss of conceptual knowledge that is not category-specific but often tied to specific properties of different concepts in different categories (Hodges et al., 1995). In line with the embodied theory, there is evidence that semantic knowledge is localized and distributed in sensorimotor areas (Hauk et al., 2004; Kiefer et al., 2008), where activation patterns can vary according to the task context (Hoenig et al., 2008), in favour of a distributed view of semantic knowledge. Of course, an existing possibility is that there is a subsequent involvement of other associative and high-order areas for integration of the representations in a supramodal way (Mahon and Caramazza, 2008; Pulvermüller et al., 2012; Simmons and Barsalou, 2003).

The third issue deals the debate about the existence of innate or experience-built categorical distinctions which guide the acquisition on conceptual knowledge. James and Gauthier (2003) in an elegant study demonstrated that the associations between novel objects and verbal labels of objects features referring to a given sensorial modality (auditory and object motion) caused the activation to the correspondent sensorial area during a subsequent matching task on the objects. Furthermore, activation of sensorimotor areas implicated in the processing of manipulable objects during novel objects perception increased with respect to a baseline condition after an interactive training, where subjects were requested to interact with the novel objects (Weisberg et al., 2007). The activation was greater if the interaction consisted to making an action pantomime towards the novel object with respect to a simple pointing (Kiefer et al., 2007).

The last question was about the stability or flexibility of concepts. This problem is directly related to the assumption that context could or could not interact with concept meaning and processing. On the one hand, basic premises of studies that investigated different neural systems for the elaboration of different conceptual categories started from the principle that these different systems worked independently from task demands and contextual changes. On the other hand, this assumption resulted problematic if we consider some basic feature of language, as for example, semantic ambiguities in the relation between words: the word "game" is lexically ambiguous as it could refer to a match or to animals to be hunted. In this view, assuming conceptual flexibility, semantic features are flexibly recruited form distributed modality-specific brain regions depending of contextual constraints (Barsalou, 1982; Kiefer, 2005). Hoenig et al. (2008) tested in a combined fMRI/ERP study the notion of concept flexibility and the involvement of modality-specific brain areas. Participants had to categorize objects attributes types (visual or action-related) for words denoting artifactual or natural objects. The study revealed that the access to conceptual knowledge was modulated by attribute type: modality-specific brain areas increased their activation during the processing of the non-dominant features (i.e. action-related attributes for natural objects). This process emerged in the earliest phases of processing (116 ms), reflecting a rapid access to semantic features rather than a post-conceptual processing.

Taking together, all these evidences gave support to the embodied theory, claiming that concepts are distributed representations grounded in modality-specific neural systems related to perception and action. These representations are the result of previous motor and sensorial interaction with physical world, and can be flexibly activated depending on a wide variety of contexts depending of our experience. Embodied theory of cognition holds all these characteristics and could be the perfect candidate to explain the complex matter of concepts manipulation.

1.2 Language representation in the sensorimotor system

When we talk about concepts, we inevitably talk about language. Words are used to speak about different types of objects, actions, feelings, etc… Words can express a concrete concept (e.g. eye, to grasp), or a more abstract concept (e.g. beauty, friendship). Language is the major vehicle through we express concepts. A large part of scientific evidence about embodied cognition concerns the question about language processing in the sensorimotor systems.

Behavioural and neurophysiologic studies in the last years demonstrated that understanding of language relies on embodiment at multilevel processing. Indeed, evidences can be divided at three-level dimension of language: embodied simulation at vehicle level, at content level and at syntax level (Gallese, 2008). Evidences about the vehicle level came from studies that demonstrated the activation of motor areas during listening of speech or observation of corresponding mouth movement (Fadiga et al., 2002; Watkins et al., 2003; Watkins and Paus, 2004). These results were interpreted as the proof of the existence of a motor resonance mechanism at the phonological level. Activation of motor areas also seems to correlate with blood flow increase in Broca's area (Watkins and Paus, 2004). It is well known that Broca's region is described as a classical area of language circuit, but it is also part of human Mirror Neuron System (hMNS, Bookheimer, 2002; Nishitani et al., 2005; Rizzolatti et al., 2014; Rizzolatti and Craighero, 2004) and is activated by the observation of either hand and oro-facial gestures (Ferrari et al., 2003; Gentilucci et al., 2006), suggesting its possible functional role in the evolution of language (Gentilucci and Corballis, 2006, see chap. 3).

Concerning the content level, in accordance with the embodied theory different studies reported the role of the same neural structures involved in action execution in the understanding of the semantic content of language.

Some brain language models attribute semantics in the temporo-occipital areas, along the ventral stream involved in the process of visual object-related information, in line with amodal theories. However, recent evidences showed that fronto-parietal areas, overlapping with the putative hMNS, are active in semantic processing. Furthermore, lesions in this part of cortex or motor degenerative diseases lead to severe linguistic-conceptual impairment, especially with concrete meaning (Bak et al., 2001; Bak and Chandran, 2012;

Gainotti, 2004; Gainotti et al., 1995; Kemmerer et al., 2012; Kiefer and Pulvermüller, 2012; Pulvermüller and Fadiga, 2010), demonstrating a causal role of sensorimotor systems beyond the correlational evidence.

Functional imaging studies described the somatotopy of semantics in precentral motor and premotor cortex, showing that words (both verbs and nouns), phrases and sentences semantically related to different parts of the body, activated the corresponding motor region: foot-related verbs (e.g., to kick) activated more dorsal part of the motor cortex whereas hand-related (e.g. to grasp) and mouth-related (e.g., to lick) activated more lateral and ventral parts (Buccino et al., 2001; Dalla Volta et al., 2014; Hauk et al., 2004). In addition, a specific perturbation on motor cortex with Transcranial Magnetic Stimulation (TMS) revealed to influence performance in a conceptual task, improving the recognition of action verbs related to the stimulated effector (Buccino et al., 2005; Devlin and Watkins, 2007; Pulvermüller et al., 2005b). In general, activation of specific motor regions in response to action verbs was demonstrated to emerge within an interval of 200-300 ms from the stimulus onset (Dalla Volta et al., 2014; Innocenti et al., 2013; Pulvermüller et al., 2005). This is in favour of the hypothesis of a direct conceptual access by means of the somatotopic activation, excluding the possibility of an accessory activation related to a response or a post-conceptual processing (for an alternative hypothesis see Papeo et al., 2009). This was confirmed also in MEG and EEG studies that found earlier signs of cortical meaning processing related to post-lexical neurophysiological index like N400, as pre-responses with a latency of 100-250 ms, thus arguing that meaning related motor activity indexes early semantic access rather than late post-understanding inferences (van Elk et al., 2010). Furthermore, a series of behavioural studies that used priming or interference paradigms evidenced how the preliminary activation of sensory or action-related representation could influence subsequent conceptual processing (Helbig et al., 2009; Kiefer et al., 2010; for a reviews see Barsalou, 2008; Fischer and Zwaan, 2008); behavioural findings confirmed the functional role of the modal activations, ruling out the possibility that the results of neuroimaging studies were only “epiphenomena” related to task-irrelevant associative processes.

The main part of discussed studies of language embodiment reported motor activation in response to processing of verbs that express concrete actions. Motor activation in response to abstract language is, however, still a matter of debate. Despite a lot of studies did not found traces of embodiment for abstract/symbolic language processing, some authors demonstrated that also abstract language can be coded in a modal way within contextual sensory-motor experiences (Kiefer and Pulvermüller, 2012; Scorolli et al., 2011; see chap. 2).

In the last instance, the activation on premotor cortex was also revealed during tasks that required syntactic analysis of language (Embick et al., 2000; Newman et al., 2003; Schubotz and Cramon, 2004) or during acquisition of artificial linguistic grammars (Friederici et al., 2006; Musso et al., 2003; Tettamanti et al., 2002). The syntactic domain of language is classified like a "narrow language faculty" (Hauser et al., 2002), because it encompasses specific aspects that are strictly related to language structure and not to meaning relations in general. Indeed, grammar and syntax are considered the main example of the human ability to process hierarchically structured recursive sequences that constitutes the basis of the infinite nativity of language, which is more than a finite combination of elements.

The involvement of premotor circuit in the acquisition and processing of these complex structures suggested some authors to speculate about a parallelism between grammar and the complex organization of the hierarchical structure of goal-related actions, suggesting an evolutionary-guided role of premotor cortex in the emergence of language syntax (Gallese, 2008; see chap. 2). The author (Gallese, 2008) proposed that the circuit within premotor system can function according to two modes of operation: in the first mode, the circuit structures action domain with connections with motor and sensory areas; this means that cortico-spinal pathway is activated following action execution, observation, imitation or imagination, through actual movement or simulation. In the second mode, the same circuit can be delinked from action perception/execution function and "exploited" to offer its functioning to master the hierarchical structure of language and thought. According to this "neural exploitation hypothesis", as motor acts of premotor vocabulary (Rizzolatti et al., 1988) are assembled and chained to form intentional complex actions (Fogassi et al., 2005), words can also assembled and chained to structure language sentences and thoughts, as the same circuit chains actions.

Chapter 2 – The debate about abstract-symbolic semantics

2.1 Embodied vs. Disembodied Semantics: an attempt to an integrated view

The huge evidence about the involvement of sensory and motor areas during semantic processes suggests a common mechanism for action, perception and language. However, the observation of disembodied semantic functions in multimodal association cortices far removed from sensory and motor fields, contradicts this view (Bedny and Caramazza, 2011). In addition, while a large amount of data evidenced an activation of sensorimotor areas (even in co-activation with associative areas) for concrete language, the question is not so clear for abstract or symbolic language. The level of "grounding" is still a major point of debate in the embodied theory, since a correspondence between language and perceivable world results crucial for sensorimotor areas involvement. This question gives strength to the classic idea of a "semantic Hub" that behaves as an integration centre where different aspects of words meaning can converge independently from their modality features. The idea of a semantic hub is in line with an amodal theory of concept processing (see Chap. 1). However, it seems not so easy to identify the area that could be the putative semantic hub. Neuroimaging and neurophysiological studies have revealed several cortical regions that may support general meaning processes:

(i) Inferior frontal cortex, or more specifically the anterior part of Broca's Area (BA 44-45 and 47) (Bookheimer, 2002; Devlin et al., 2003)
(ii) Superior temporal cortex, or the classic Wernicke's Area (Dronkers et al., 2004; Hillis et al., 2001; Lichteim, 1885; Wise et al., 2001).
(iii) Inferior parietal cortex, angular and adjacent supramarginal gyrus (Binder and Desai, 2011; Bonner et al., 2013; Geschwind, 1979), involved in semantic processing of cross-modal spatial and temporal configurations.
(iv) Inferior and middle temporal cortex (Poeppel et al., 2012; Price, 2000), supported as general binding site between words and their meaning;
(v) Anterior temporal cortex, selectively impaired in semantic dementia deficit (Mion et al., 2010; Patterson et al., 2007b; Tsapkini et al., 2011).

Interestingly, all these brain areas seem to contribute differentially to the meaning processing. Indeed, they are activated to different degree on the basis of the semantic features of the word processed. Consequently, words that belong to a specific semantic category may be more or less impaired depending of the focus of a brain lesion. For example, action-related verbs processing resulted more impaired in case of lesion of left Inferior Frontal Cortex (IFC) and bilateral fronto-central motor systems (Bak et al., 2001; Kemmerer et al., 2012; Pulvermüller and Fadiga, 2010), while the left supramarginal gyrus lesions affected more spatially related language, including prepositions (Kemmerer, 2006; Noordzij et al., 2008). Angular gyrus and intraparietal sulcus are also areas of special importance for processing of number concepts (Dehaene et al., 2003; Tschentscher et al., 2012). Finally, different parts of middle/inferior temporal cortex, more adjacent to the ventral system, showed category-specific effects for animal, tool or colour and form-related words (Damasio et al., 1996; Gainotti, 2010; Martin, 2007).

On the basis of these studies, the content of a concept results strictly related to its processing. In this way, a more flexible view in line with embodied principles (Kiefer and Pulvermuller, 2012, see chap.1) results more plausible than a classic amodal view that see stable concepts related to each other without considering their form.

Pulvermüller (2013) suggested an integrative view of neurosemantics that covers both embodied and abstract-symbolic processes, in both modality-specific and multimodal areas of the brain, spelling out about semantic processes that can explain the constitution of the link between actions to abstract concepts.

A first explanation given from the author concerns the distributed location of the semantic brain processes of the brain. A neural key could be the correlation-learning principle in neurophysiology: neurons that fire together, wire together. The proposal is that the connection between the areas involved in the pronouncing of words (i.e. articulatory motor system) and the areas involved in the perception of words and mouth movement (auditory system in temporal cortex and somatosensory systems) could have supported fronto-temporal connections that resulted in the spoken language circuit localized in the perisylvian cortex, with an important contribution of motor areas (Rizzolatti and Arbib, 1998). Likewise, correlation between words and sensorial (i.e. sound, form or colour) or action-related information related to them, could have led to the establishment of embodied referential semantic circuit that includes perisylvian areas and circuits in sensory and motor cortex; this explains results about category specific semantic grounding (Kiefer and Pulvermüller, 2012; Pulvermüller and Fadiga, 2010).

Pulvermuller (2013) also addressed the problem of the activation of multimodal areas outside sensory and motor systems mentioning the mechanism of cortical connectivity. For activity to travel between auditory and motor cortex, a number of areas need to be traversed (Rilling et al., 2008) as for the connection between visual cortex and language areas via interlinking relay "hubs" in temporo-occipital and middle temporal cortex (Bullmore and Sporns, 2009). In conclusion, to link the spoken word form "grasp" to the concordant motor movement, or the articulation of the word "grass", and to specific visual knowledge about its colour and shape, nerve cells in motor and sensory cortex are necessary; in addition, intermediary area neurons are equally required to build circuits that bind sensory and motor information, that is "semantic grounding" (Pulvermüller, 2013). This mechanism explains the differential activation of different cortical areas depending on the content of the concept, and support both embodiment and disembodiment at the neural level.

Another or parallel explanation could be the existence of a mechanism of "combinatorial semantics". Combinatorial models express meaning similarity in terms of the probability of the co-occurrence of words with other words in the same sentence, or in general, in the same context (Landauer, 1998).

Considering the case of action-related language, it is possible through this kind of "contextual learning", the formation of a secondary grounding (or "symbolic theft" in neural networks, Cangelosi and Harnad, 2001), where novel words were associated to embodied referential representation previously learnt. More specifically, the agent could acquire new grounded concept in a primary way through direct sensorimotor interaction with the environment, and in a secondary way through the hearsay of propositional combinations of previously grounded symbols. In symbolic theft, the symbol grounding transfer mechanism permits the transfer of grounding from directly grounded symbols to new words.

For example, if an individual has learned the meaning of the symbols “horse” and “stripes” through direct experience with their referents (horses and striped patterns), she could also indirectly ground the meaning of the symbol “zebra” from a propositional definition such as “a zebra looks like a horse with stripes”. This is possible through the transfer of the grounding from the basic symbols to the newly acquired word.

In neural terms, the co-occurrence probabilities of words could be mapped in the language circuit in perisylvian areas, because in these areas all words can share combinatorial “disembodied” information. This is an alternative hypothesis that supports the role of a multimodal convergence zone in addition to the activation of sensory and motor areas.

2.2 Grounding abstraction: evidences and future directions

The abstract-meaning debate constitutes the core of the arguments that contrast an embodied view of language and that claims about the necessity of an amodal-meaning system.

An embodied-semantic link was proposed for abstract words expressing emotions. In fact, it was demonstrated that abstract terms show an over-proportionally tendency to be linked to knowledge about emotion (Kousta et al., 2011; Meteyard et al., 2012). The grounding level of abstract words in emotion was empirically evidenced through the activation of motor cortex with somatotopy congruent with emotion-expressing body parts, in response to abstract emotion words (Moseley et al., 2011; Proverbio et al., 2014). Thus, at least for this category of abstract concepts, the interaction with external world through perception and action sounds important to learn the association between symbols and action schemas that represent the expression of the corresponding emotion.

A specific feature that characterizes abstract words and makes more problematic the developing of a common model with concrete words is the grade of “variability” or lexical flexibility. The main part of words related to concrete concepts may be related to a unique referent or prototype (e.g., eye), that is a best representative schema. Even with some variants (in form, colour, or size) the schema is always easily associated to the words. This is not always true for abstract words: in some cases, abstract words can refer to different prototypes. For example, considering the case of the word “game”, which can refer to different kinds of activities and no single prototype can represent all of the action schemas that can be referred to it. This is probably the cause of the different brain correlates found for different subtypes of abstract words (Binder et al., 2005; Boulenger et al., 2009). Because of the level of variability, an abstract concept that can be grounded in a specific schema results detached from specific action-perception knowledge. At the neural level, if we take in account the correlation-learning hypothesis, the link between associative and motor areas could result weak with respect to concrete representations. At the same time, the development of a semantics that includes concepts not strictly bind to specific contents and that can be modulated by context could be the key question that can explain the existence of an associative relay area for multimodal semantic processing. Indeed, strictly related to the dimension of variability is the role of context. It was demonstrated that abstract words integrated in a concrete context can activate sensorimotor regions (Boulenger et al., 2009; Lauro et al., 2008; Sakreida et al., 2013; Scorolli et al., 2011). This means that including an abstract concept in a definite context can reduce the grade of variability, facilitating the link with a specific sensory-motor schema.

In this view, an interesting issue was the possible role of learning. We supposed that, on the basis of what reported previously, the grounded semantics related to abstract concept is the result of previously learnt associations. More is the number of these associations, more variability we can expect. Thus, acquisition of concrete and abstract language could involve different processes, one more related to interaction with physical world and the other more based on built linguistic relations.

A recent theory that takes in account these points is proposed by Borghi and Cimatti (2009) in “Word as Social Tools” (WAT) proposal: authors evidenced the social role of language and its potentially role in learning of abstract concepts. Proposal extends embodied views assuming two simultaneous cognitive sources for word meanings; an individual one, the embodied individual experience, and a socially embodied one. While for words having a concrete referent labels are “attached” to concepts formed on the basis of sensorimotor individual experience, in the case of meanings of abstract words the cognitive source is still embodied, but primarily in the use of the social word/tool. Thus abstract words represent a means to collect a variety of sparse bodily and situational experiences. Recent studies reported scientific evidence in favour of this proposal through the investigation of learning mechanisms involved during acquisition of concrete and abstracts novel concepts (Borghi et al., 2011; Granito et al., 2015).

With chapters 1 and 2, I introduced the theoretical framework of embodied cognition and a large amount of scientific evidence about the involvement of sensorimotor system in conceptual processing and more specifically in language processing. Furthermore, I reported the latest evidences and theories about the integration of embodied and disembodied processes, with particular care to the problem of the semantic comprehension of abstract word in modal areas.

In the successive chapter I will deal the major issue of the origin of language starting from the motor theory point of view and discussing it in an evolutionary perspective. Then, I will present studies about the relations between language and manual gesture, presenting behavioural and electrophysiological evidence from the interplay between transitive action and vocal spectra and about the integrated processing of symbolic gestures and corresponding-in-meaning words. Symbolic gestures represent the more conventionalized aspect of manual movement and constitute the “modal” representation of symbolic concepts. It can be delivered in utter silence because it replaces the formalized, linguistic component of the expression present in speech (Goldin-Meadow, 1999; Kendon, 2004; McNeill, 1992, see chap. 3). The study of this level of action/language understanding is fundamental to raise a general comprehension of the interplay between manual action and language at each level of grounding.

In the last instance, I will present three novel studies that have faced the problem about gesture and language integration and the role of sensory-motor systems in the comprehension of the two communicative signals.

Chapter 3 – The origin of language: from the motor theory to the relation between gestures and words.

3.1 The origin of language: from manual gestures to speech

The question about the origin of language is still far to be solved. Different theories have tried to explain when and how spoken language appeared in the phylogenetic story of humans and how it evolved until to represent itself with the characteristics that we know in the present day. Chomsky (1986) considered language as a “big bang” of human’s evolution. Language would be appeared suddenly during evolution because of a lucky mutation in the DNA, and it is not derived from previous communication modalities. Pinker (1994) proposed that the genetic predisposition of humans to language was integrated with an evolution of linguistic abilities gradually formed by a natural selection. Following the theory of Jackendoff (2002, 1996), our language was the result of the gradual evolution of different partially independent subsystems, differently related to the phonetic, the meaning, the combining ability etc., that were subsequently integrated to constituted the language as we know it today.

Gentilucci and Corballis (2006) postulated that language evolved starting from an initial primitive communication system based on the use of manual gestures; subsequently, the gradual introduction of mouth gestures and vocal elements, initially coupled with manual gestures, could have permitted the gradual development of speech.

In support of this claim, the theory of Articulatory Phonology of Browman and Goldstein (1995, 1989; Goldstein et al., 2006), which expands the initial theory of motor perception of speech (Liberman and Mattingly, 1985; Liberman et al., 1967) describes speech as a “gestural system” that can be perceived not like a totality of listened phonemes but like a set of mouth and tongue postures (or gestures) and movements that can origin a lot of vocal sounds. The motor theory (Liberman et al., 1967) assumes the necessary and crucial role of motor system in detecting speech.

The development of a communication system with these features and based on the perception and execution of mouth and manual gestures, could have been sustained during evolution by a system with peculiar characteristics that would have constituted the instrumental neural substrate of language processing: the

Mirror Neuron System. The Mirror System is mainly involved in action understanding (Gallese et al., 1996; Rizzolatti et al., 2014; Rizzolatti and Craighero, 2004) through its property of matching observation with execution of motor acts through a "simulation" of the actions. This mechanism creates a link between an agent and an observer, whose act like a sender and a receiver of a message in a communicative context. The simulation mechanism in this sense could have been the ground for communicating manual and vocal messages. Furthermore, the capability of human MNS to understand not only transitive actions, but also complex pantomimes and intransitive movements, could have permitted respect to non-human primates, the development of a complex and symbolic communicative system, not strictly related to the physical world, as the human language is (Arbib, 2003; Rizzolatti and Arbib, 1998).

Focusing on the experimental evidences, two class of neurons recorded in monkeys in the premotor area F5 (one of the focus area of MNS circuit) were identified as the possible neural substrates that were functionally involved in the speech development. First of all, a large amount of evidences demonstrated the homology between the area F5 of monkeys and the Broca's area or BA 44-45 (Passingham, 1993; Petrides and Pandya, 2002; Rizzolatti and Arbib, 1998; see Fig. 2). Broca's area was the first area identified as responsible of language production (Broca, 1861), and I already reported a lot of evidences that demonstrate its main role in language processing (see Chap. 1). The first class of neurons were recorded in the homologue area in monkeys (F5) and showed mirror properties (Gallese et al., 1996) since it was activated in response to the observation of action executed by the experimenter; this mechanism of motor simulation could have constituted the neural prerequisite for the development of interindividual communication, initially through manual and facial gestures until the introduction of vocalization and at the end, speech. In support of this hypothesis a group of neurons of this class showed mirror response not only after the observation of manual and mouth actions but also to oro-facial communicative gestures (Ferrari et al., 2003). Note that despite a mirror system for vocalization has not be found, neurons discharging during voluntary rather than spontaneous vocalizations were recorded in monkey ventral premotor cortex (Coudé et al., 2011), confirming the possible central role of this area in rudimental language development. Probably, vocalization intervened later in evolution, when the relations between mouth and hand were consolidated at level of postures (Corballis, 2012). Indeed, observation of grasp actions showed to influence the simultaneous pronunciation of syllables in humans (Gentilucci, 2003b; Gentilucci et al., 2009, 2004a, 2004b).

Andric and colleagues (2013), in a neuroimaging study on humans reported overlapping activations in the areas belonging to the mirror circuit in response to:

1. the observation of manual symbolic gestures (like “Ok”, or “thumbs up”) and speech listening in the left inferior frontal gyrus (BA 44 and 45);
2. The observation of manual symbolic gestures and transitive actions in parietal and premotor areas (mirror circuit).

These results suggested the activation of different circuits depending from the coding mode (modality-oriented or meaning-oriented) that occurred independently from the presentation modality (manual vs. verbal). This is a clear evidence of the involvement of mirror circuit in human communication, and of the strict relation that ties language and action.

The second class of neurons recorded in monkey’s F5 could be more instrumentally involved in the gradual transition from manual to oro-facial gestures and, at the end, to speech. This class of neurons showed response during the execution of actions performed with the hand or mouth, both with controlateral or ipsilateral effectors (Rizzolatti et al., 1988). The function of these neurons was interpreted as a coding of the goal of an action, independently from the effector used, and consequently as commanding successive motor acts performed, for example, with hand and mouth. Indeed, in the case of the study of Rizzolatti and colleagues (1988), the goal was to grasp a fruit with the hand and bringing it to the mouth with the intention to eat it. A possibility is that the motor command of grasping could be transferred from the hand to the mouth in order to prepare the effector to receive the food grasped with the hand. Several studies on humans of Gentilucci and colleagues (Gentilucci, 2003a, 2003b; Gentilucci et al., 2009, 2008, 2004a, 2004b, 2001; Gentilucci and Campione, 2011) demonstrated this hypothesis describing the relation between the kinematics of hand and mouth movements during the execution of reaching and grasping action of an object, executed simultaneously to a mouth aperture or a vowel pronunciation. Results showed that more was the increase of finger aperture during hand grasping (related to the dimension of the graspable object), more was the mouth aperture and the increase of vocal spectra during the vowel pronouncing, and vice-versa. The same effect was obtained even if the hand grasping or the mouth grasping were simply observed by the participants (Gentilucci, 2003b; Gentilucci et al., 2004a, 2001). Furthermore, the effect is maintained also in response to the observation of the simple static posture of hand/mouth aperture (Gentilucci and Campione, 2011). This relation was demonstrated also at neurophysiological level measuring Motor Evoked Potentials of the tongue muscle through the stimulation of the primary Motor Cortex (M1) with the technique of Transcranial Magnetic Stimulation (TMS). Tongue MEPs increased their amplitude in response to larger grip size during the observation of grasping pantomimes depicting whole or precision prehensions (Gentilucci et al., 2009).

The functional relation between hand and mouth emerged not only during execution/observation of transitive actions, but even during execution of intransitive gestures, in particular iconic gestures representing size (Gentilucci et al., 2012). In the study of Gentilucci et al. (2012) participants were presented with iconic gestures depicting a dimension (SMALL or BIG, that could be unimanual or bimanual) and then they were required to pronounce a vowel (/a/ or /i/) or a word related to the dimension (/grande/ or /piccolo/, “big” or “small” in English). The first result was that the vocal spectra of the pronounced vowel /a/ (which the pronunciation is related to a larger aperture of the mouth) increased in response to observation of the gestures depicting the big dimension, executed either in unimanual or bimanual way. This result demonstrated the existence of the mechanism that couples hand and mouth postures related to the dimension also for intransitive gestures. The second result was the increase of the vocal spectra of the vowel /a/ included in the word /grande/ only in correspondence of the bimanual “big” gesture. In this case, the result suggested a more complex mechanism, probably based on the semantics conveyed by stimuli when the gesture and the pronounced word were congruent in meaning.

The modulation of the vocal spectra was based on a communicated meaning (in this case, the size) not obligatory related to a physical property, as commonly we communicate using speech. This is an elegant demonstration of the relation between manual gestures and speech at a basic posture level and at a more complex symbolic level. The results of these kinds of studies are the best candidates to explain the gradual transition from transitive actions to speech. In other terms, the system that transfers the meaning of transitive actions to speech (Gentilucci et al., 2009) might have provided the basis for the evolution of a system relating **GESTURES** and **WORDS**. Especially symbolic gestures (i.e. “thumbs up”) represent the conjunction point between manual action and speech (Andric et al., 2013; Andric and Small, 2012). The study of interaction between symbolic gestures and speech could finally shed light to the complex question about the origin of language, and say more about the involvement of mirror system in the development of speech, and consequently, of human social cognition.

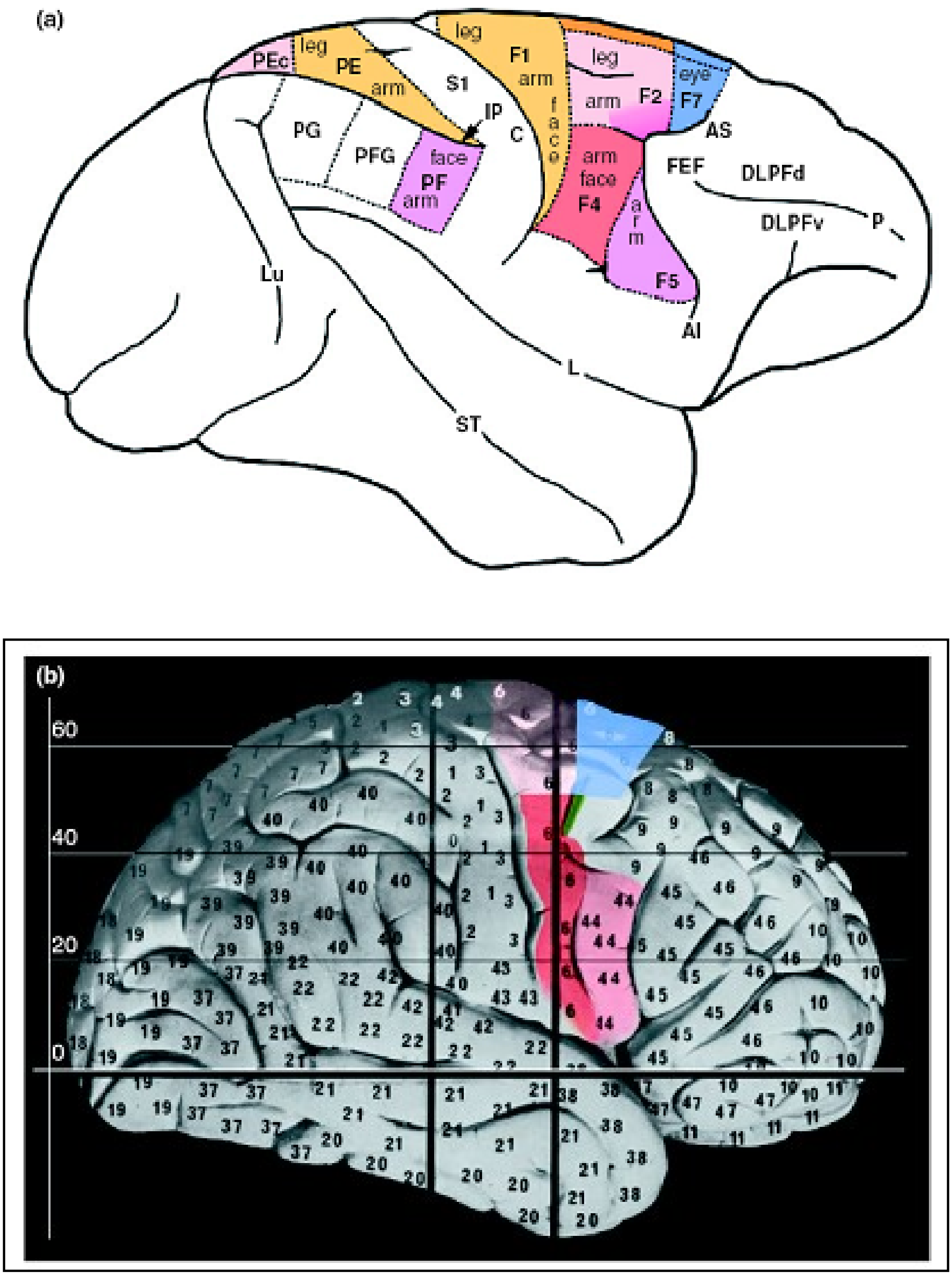


Figure 2: *Lateral view of monkey cerebral cortex (Panel A) and human cerebral cortex (Panel B). Rizzolatti & Arbib (2008) proposed that BA 44 in humans is the homologue of area F5 of the premotor cortex of monkeys and that the lateral BA6 phylogenetically correspond to the area F4 of the monkeys (adapted from Gentilucci et al. 2008).*

3.2 Gestures and speech: theories

In every culture, with some minor differences, gestures are used concurrently to speech or in place of it. Gestures clearly constitute a fundamental feature of human communication. Gestures have not only the function to give a concrete representation of the object or the topic of a communication but they can also contribute to specify the propositional content of the message (Kendon, 2004). At the ontogenetic level, they seem to be the precursors of language development (Bates and Dick, 2002; Iverson and Goldin-Meadow, 2005; Masataka, 2001).

Kendon (1982, 1988, 1997), classified human gestures on a hierarchical continuum (Fig. 3) based on the grade of necessity of the contemporary presence of language for the disambiguation of the gesture meaning in case of the execution of the gesture alone. At the bottom of the continuum there are the gesticulations, spontaneous arms and hands movement not conventionalized in culture and always accompanied by speech. One step over there are the pantomimes (mimed actions), followed by symbolic gestures (or emblems, gestures conventionalized in cultures) that occur frequently alone in substitution of words. Lastly, at the top, there are the signs, that constitute an independent linguistic system with own rules.

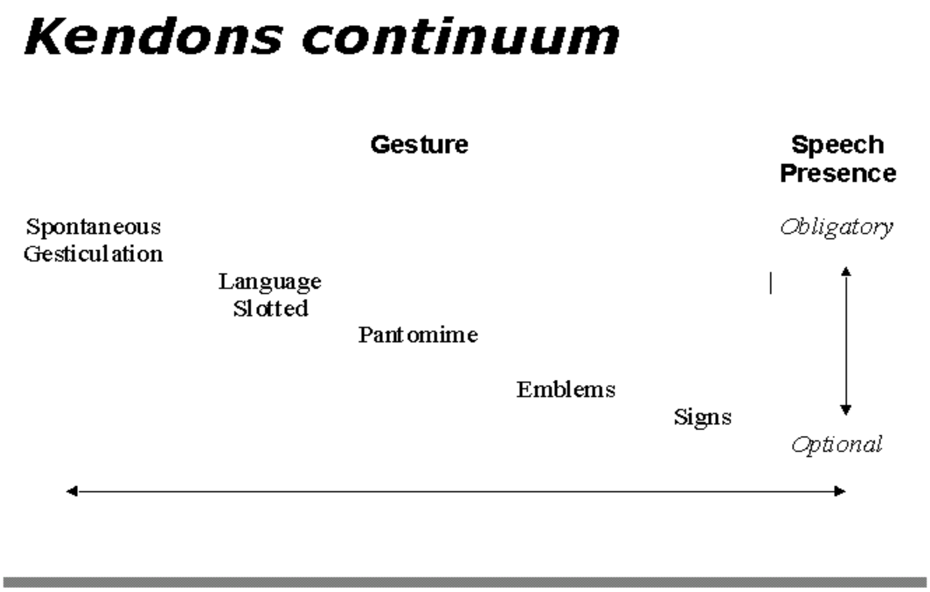


Figure 3: *Kendon's continuum (Kendon, 1982, 1988)*

Gestures can also be classified on the basis on the functional interpretation of the content in relation with the communication context (McNeill, 1992). This classification proposes a class of gestures defined as "representational", namely gestures where movements are executed with the aim to visually represent an object form, (i.e. gestures representing size), or a pattern of movements representing a iconic or metaphorical concepts. In the class of non-representational gestures, we can find "deictic" gestures (e.g., pointing gestures) and "beat" gestures, which are rhythmic movements usually coupled with speech as gesticulations.
In the first classification it was emphasized the communicative function of gesture, while in the second the author focused on the representational function of the content. Symbolic gestures (or emblems) are the one that best formalizes the "linguistic" content of speech and so could be the best candidates as substitute of language, except for the expression modality (manual vs. verbal). The system that relates transitive actions to syllables might provide the basis for the evolution of a system that relates symbolic gestures to words. Words, like symbolic gestures, bear little physical relation with the objects, actions, or properties they represent. In fact, a process of conventionalization (Burling, 1999) may be responsible for transforming meaningless gestures (i.e. gesticulations) into symbolic ones as well as string of letters may be transformed into a meaningful word. For this reason, a large amount of behavioural and neurophysiological studies have tried to investigate the neural processes involved in the processing of emblems, and their functional relations with speech. Knowing more about emblems and words, could add the "missing link" that can explain the transition from manual to verbal communication in humans. Prior to present the main results of the more recent studies about gesture and language, it is worth to outline the rational theories that tried to formally explain the undeniable relation that exists between them.
Two major models, one opposed to other, predominate in the recent literature: the first is the **theory of independent communication systems** (Krauss & Hadar, 1999) that claims that gestures and speech belong to two different communicative systems that work separately and are not integrated each other. Communication with gestures is described as an auxiliary system, evolved in parallel to language, that can be used when the primary system (language) is

difficult to use or not intact. In this view, integration of gesture with speech is regarded as a post-lexical process, taking place only after semantic processing of the verbal and gestural message has occurred. In other words, they are integrated with each other after becoming amodal representations. The **theory of integrated communication systems** instead, proposes that gesture when accompanies speech is seen as an integral part of meaning construction (Kita, 2000; McNeill, 1992). The integrated hypothesis is centred on the idea that language comprehension initially can involve the same processes that specifically may engage neural systems for perception and action. Consequently, speech and gesture may be initially both represented in motor domain, that is in modal terms, and they have to necessarily interact during lexical-semantic processes. This theory is consistent with the idea that concepts are embodied and supports the central role of MNS in language processing and in the development of oral communication.

In conclusion, in order to demonstrate the validity of the Integration Theory, it is necessary to investigate the reciprocal influence of gestures and word during their production and semantic understanding, to underline the cortical areas involved in this processes and to clarify the critical role of the sensorimotor system, as primarily evidenced for transitive actions understanding. In the next paragraph, I will review the principal evidences of behavioural and neurophysiological studies that claimed the gesture-speech integration. The main part of these studies used symbolic gestures for the reason explained before: they shared the modality of execution (manual) with transitive actions and the symbolic meaning with language (Andric et al., 2013).

3.3 Empirical evidences of integration between gestures and words

Behavioural studies conducted by Gentilucci and colleagues showed the first evidence about a strict relation between gesture and language in terms of integration between the two modalities. With the term "integration" they referred in this case to a modification of the parameters of one communicative signal (e.g., vocal spectra of word pronunciation) caused by the influence of another communicative signal with different modality (e.g. a manual symbolic gesture). In the study of Bernardis & Gentilucci (2006), participants were presented with written words which meaning corresponded to a symbolic gesture, like CIAO (“hello”), NO, and STOP. They were requested to respond to the presentation of the written word with different task: a) to repeat aloud the read word b) to execute the gesture corresponding to the meaning of the word, and c) to execute the gesture corresponding to the meaning of the word and contemporary to pronounce aloud the word. Furthermore, in two control conditions participants were requested d) to pronounce aloud the word and to execute a meaningless gesture, and e) to execute the corresponding-in-meaning gesture but to pronounce simultaneously a pseudoword phonologically similar to the word (e.g. /lao/ instead of “ciao”). Results showed that when gesture and word congruent in meaning were produced simultaneously, the vocal spectra related to the pronunciation of the word (in particular the formant 2 of the spectra) increased respect to the condition where the word was pronounced in isolation. Conversely, in the same condition, kinematic parameters related to the execution of the gesture decreased respect to the condition where gesture was executed alone. These effects were not present in the case of simultaneously production of meaningless gesture or pseudoword, suggesting that the mechanism was selectively involved in meaning processing. Furthermore, in a later study of Barbieri and colleagues (2009), it was demonstrated that the effect on vocal spectra and gesture kinematics was not maintained in the case of production of two communicative signals incongruent in meaning. The functional interpretation given by the authors about of the results of the described studies followed the theory that proposes a common mechanism of motor control of hand and mouth: the idea was that the system which controls gesture execution gave facilitators commands to the system that controls the mouth movements, involved in the pronounce of word that corresponds in meaning to the gesture. Subsequently, this system would act retroactively on the hand control, but inhibiting the gesture execution because of a redundancy of this communicative signal.

Leoni and Maturi (2002) proposed that considering that vocalizations require particular postures of the internal/external mouth, different ranges of frequency that characterize the vocal spectra during vowel pronunciation, described as “Formants”, can give indications about the posture of internal mouth. In particular, Formant 1 (F1) increase corresponds to internal mouth aperture, while Formant 2 (F2) is an index of tongue protrusion.

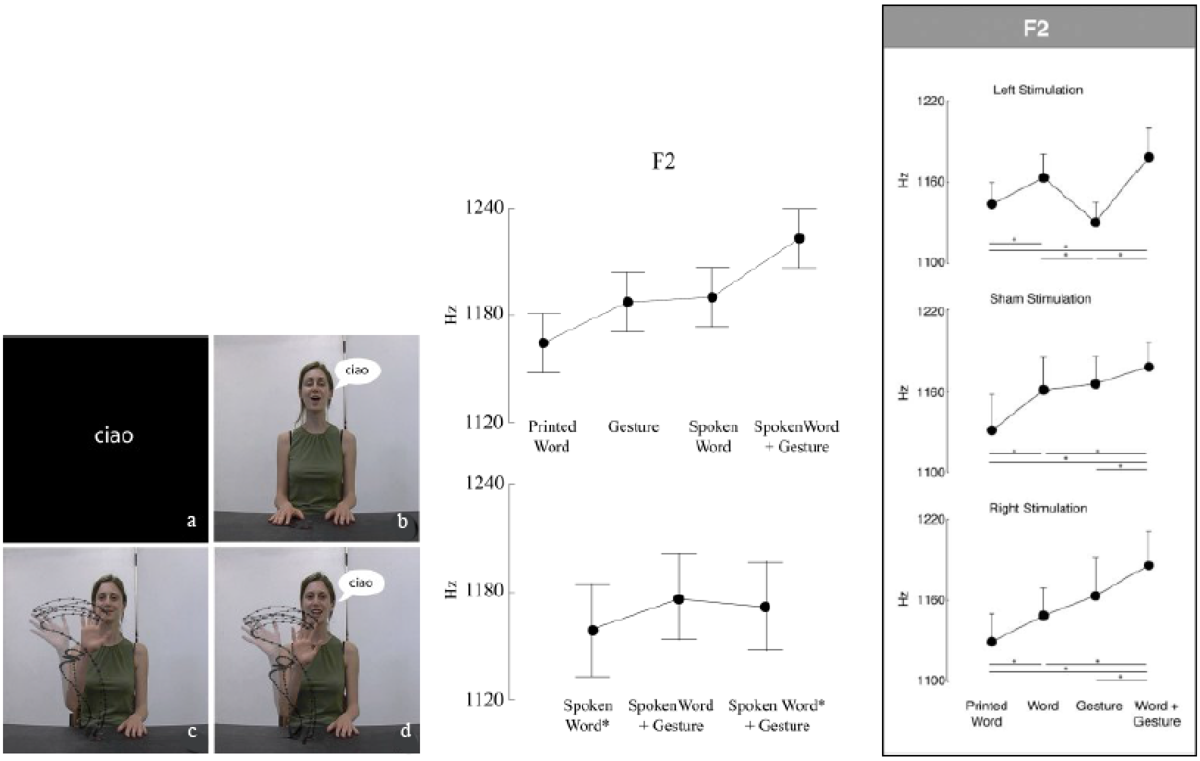
In a second experiment reported in the study of Bernardis and Gentilucci (2006), authors investigated how the response to communicative symbolic gestures or words presented with different modalities could change; the three stimuli (CIAO, NO, STOP) were presented in three different conditions: a) a word presented on a black screen b) a video with an actress who pronounced aloud the word c) a video with an actress who executed the corresponding gesture and d) a video with an actress who simultaneously executed the gesture and pronounced the words. The task of the participants was to pronounce the word corresponding to the meaning of the observed stimulus, independently of the presentation modality (only word, only gesture or gesture plus word). Results were in line with experiment 1: the F2 of the vocal spectra related to the word pronunciation increased in response to the condition "gesture plus word", respect to the conditions where word or gesture were produced in isolation (Fig. 4). Not less important, F2 increase was also measured in response to the only word or the only gesture observation in comparison to the baseline condition where only the written word was presented without any actress presence. This suggests a social relevance of the mechanism matching gestures and words: the increase of F2 could be explicative in this sense: F2 was related to increase of tongue protrusion (Leoni and Maturi, 2002) that is observed in non-human primates as an index of social approach. For example, lip smacking, accompanied by tongue protrusion, precedes grooming actions among monkeys (Van Hooff, 1962; 1967). Conversely, the presence of a speaking and/or gesturing interlocutor may have primed in observers the (social) intention to a direct interaction. During gesture observation, it is possible that the corresponding hand motor commands are simulated through the mirror system similarly to what happens for transitive actions. This command, through the system that coupled hand and mouth control (Rizzolatti et al., 1988; Gentilucci & Corballis, 2006), could be sent to the mouth effector modifying its articulatory posture and causing an increase of vocal spectra.

The described studies demonstrated the integration of gesture and words at behavioural level during their simultaneous production. In addition, even the observation of a conspecific that executed a gesture or pronounce a word modulated the vocal spectra of the production of word semantically related to the communicative signal observed; the increase was greater if the two signals were presented simultaneously. Therefore, the simultaneous production of gesture and words is a condition that facilitates integration. However, the data did not show if one communicative signal could influence another one if they are presented in succession. Vainiger et al. (2014) dealt with this issue though the administration of a semantic priming paradigm where gestures with or without meaning were presented as prime stimuli and words (congruent and incongruent in meaning with gestures), or pseudowords were presented as target in rapid succession. The authors measured as dependent variable the response times in three different tasks that differed each other on the basis of the level of “cognitive load”: a) a naming task, where participants were requested to simply denominate aloud the target, b) a lexical-decision task, where participants had to decide if target was a word or a pseudoword, and c) a relatedness-judgement task, where they had to judge the semantic congruency between prime and target stimuli. Results showed a facilitation effect, and consequently faster response times, when prime and target were congruent in meaning respect to the condition where prime or target were meaningless stimuli: this effect, however, was present only in the naming and lexical decision tasks. When the task was more demanding, as in the relatedness judgement decision, response times were faster when prime and target were incongruent, maybe because deeper was the analysis of the first stimulus, greater was the interference during the processing of a second stimulus related to the prime.

Another problem regarding gesture and speech is the identification of the brain areas responsible for their integration. This information is crucial to support a modal processing in sensory-motor areas of the two communication signals or an interaction at post-lexical level that occurs in associative areas more related to semantics and language understanding.

Willems et al. (2007) investigated the neural network involved in the integration of semantic information in speech with that of iconic gestures using fMRI. They found that premotor area (BA 6) was specifically modulated by gesture information that ‘‘mismatched’’ with language context. Moreover, they observed an increase of integration load of both verbal and gestural information into a previous presented speech context in Broca’s area and in the adjacent cortex (left inferior frontal cortex, BA 45/47; see also Xu et al., 2009). A large amount of neuroimaging studies reported the role of this area in action and language processing (Buccino et al., 2001; Decety et al., 1997; Gallagher and Frith, 2004; Grafton et al., 1996; Grezes, 1998) and this could be the crucial neural site where some aspects of gesture representation and consequent social intention were translated to speech articulation.

In support of this claim a study of Gentilucci and colleagues (Gentilucci et al., 2006) used a low frequency rTMS protocol (1 Hz) to study the role of left inferior frontal gyrus (IFG) in the integration between gestures and words. The study of Gentilucci et al. (2006) started from the paradigm already used in Bernardis & Gentilucci (2006): the aim of the study was to measure the modulation of the F2 parameter following the inactivation of the left IFG with respect to two control conditions, sham stimulation or the stimulation of the right IFG. The task requested to participants was the same of that of Bernardis & Gentilucci (2006), which was to pronounce aloud the word semantically congruent to the signal observed. The crucial result was the disruption of the F2 effect in response to the observation of the gesture-word and only-gesture conditions, during the left stimulation (Fig. 4). The effect of stimulation was not present if a colour name (e.g. “yellow”) was presented in place of the word congruent to the gesture meaning, confirming a peculiarity of the integration mechanism between communicative and semantic-related signals.



A B C

Figure 4. A. *Modality of stimulus presentation* B. *Mean values of formant 2 (F2) of the words pronounced in response to the stimuli presented in A. The modalities were the following: printed word; spoken word*; gesture; spoken word and gesture; spoken word* (with the actress's voice of the spoken word* condition) and gesture. (adapted from Bernardis and Gentilucci, 2006).* C. *Effects of rTMS on Broca's area, sham stimulation and right rTMS on F2. Bars are SE (adapted from Gentilucci et al., 2006).*

The results of these studies support the integration hypothesis of gesture and speech and the crucial role of IFG in this process, despite the low resolution of the rTMS could not answer to the question about a specific modal lexical access for gesture and words processing. Subsequent studies replicated this result showing the activation of IFG during gesture and speech processing (Andric et al., 2013; Ferri et al., 2014; Villarreal et al., 2008), while other contrasted this result (Fabbri-Destro et al., 2014). Indeed, Fabbri Destro and colleagues (2014), investigated gesture and speech integration by mean of EEG technique, analyzing the amplitude of the event-related potential N400, a neurophysiological index strictly related to semantic processing (for a review see Lau et al., 2008). Prior EEG studies have already demonstrated the N400 sensitivity to the semantic relation between a gesture and a word: Kelly et al. (2004) found a stronger deflection in ERPs (N400 effect) if a representational gesture expressing a physical property (e.g. height or weight) was preceded by a word expressing a different property. Other studies (Holle and Gunter, 2007; Özyürek et al., 2007; Wu and Coulson, 2007) confirmed an N400 effect for semantic incongruence between word and gesture. The strong point of the study of Fabbri-Destro et al. (2014) was the identification of the neural source of the ERPs, giving an answer to the possible neural localization of the integration process, exploiting the good temporal resolution of the EEG technique. In this study, participants were administered with a semantic priming paradigm where symbolic gestures were presented as primes and congruent or incongruent words were presented as target. The task was to judge if the prime and the target were congruent in meaning or not. The results of this study confirmed larger amplitude of the N400 for the incongruent with respect to the congruent pairs. The topographic analysis of the ERPs by mean of microstates analysis (Lehmann et al., 1990), revealed two different clusters of activity in the temporal window of the N400 effect (380-450 ms after the onset of the target); the first cluster was peculiar of the incongruent condition while the second cluster was common either to the congruent or incongruent condition. The source analysis of the latter revealed an activation of the left anterior temporal cortex (ATL), while the source of the former was localized in the left middle temporal gyrus (MTG), as well as the left posterior temporal sulcus (STSp) and the left superior parietal cortex (SPC).

It is possible that the activation of STSp and MTGp reflected the storage of the target word occurring when symbolic gesture was incongruent with it. Indeed, while in the congruent condition the gesture served as semantic priming, allowing a rapid semantic perception of the word meaning, in the incongruent condition the word meaning is needed to be represented and stored separately from gesture meaning. The activation of posterior temporal cortex was interpreted as the marker of this different processing, probably contributing to higher N400 amplitudes.

These findings and explanations are also in line with the fMRI study by Willems et al. (2009), who found greater activity of left STSp and MTGp when the speech was accompanied by incongruent pantomimes than when the same speech was accompanied by congruent ones. Whereas posterior temporal areas have been implicated in lexical-semantic storage, the anterior temporal cortex seems to support basic combinatorial operations that underlie linguistic processing and semantic integration with context (Lau et al., 2008). However, the activation of the anterior temporal region was present for both conditions: when the word was congruent with the gesture, the activity of this region lasted for the whole duration of the N400 wave. Conversely, when the word was incongruent with the gesture, activity of this region followed the posterior temporal / parietal activation. On the basis of these findings, the activation of anterior temporal region resulted to be necessary for both congruent and incongruent conditions, probably reflecting a crucial role in integrating semantics of the target stimuli (word) with the context (prime). The timing of this activation in incongruent condition resulted to be successive to that of congruent condition, supporting the hypothesis of a previous lexical-semantic retrieval of the new concept not related to the prime.

Summing up, there is no according in literature about the brain regions primary involved in the integration between gestures and words. Some studies suggest a causal role of the IFG, while others evidenced the activation of the anterior temporal lobe, or both of them. We must not forget that inferior frontal and temporal cortex classically represent the core of the linguistic neural circuit and are both involved processing and producing language. Subsequent studies will have to clarify the contribution of these two areas, since it is plausible that both of them take part in the complex process of gesture and words processing, probably at a different functional levels (see Pulvermüller, 2013).

The difficult definition of the areas involved in gesture and words interplay also depends from a not clear description of the temporal dynamic of the integration process. Gentilucci and colleagues (Bernardis & Gentilucci, 2006; Gentilucci et al., 2006) demonstrated that behavioural integration occurred when the two communicative signals were reproduced or observed simultaneously; It is not clear, if this integration occurred even if the two signals are presented or produced in succession and, if it is the case, which are the temporal constraints of this process.

A lexical-semantic effect for gesture and words presented in succession was already measured by Vainiger et al. (2014), but not vocal or kinematic parameters were analyzed by the authors.

Fabbri Destro et al., (2014) reported that interaction at semantic level exists when gesture and words where presented in succession. However, the dimension related to the amount of time of this succession was not investigated. This variable is usually manipulated in priming paradigms using different SOAs (Stimulus Onset Asynchronies) between primes and target (i.e., changing presentation timing and inter-stimulus interval). Results of previous EEG studies using only linguistic stimuli showed IFG activation with longer SOAs and MTG activation with shorter SOAs (Lau et al., 2008). However, the duration of the lexical-semantic process could not be the same for gesture and word, and, moreover, since the gesture is a manual and dynamic movement, it is difficult to establish when its meaning could be understood. For transitive actions, this seems to occur in the final phase of presentation, when the hand is assuming the final posture (De Stefani et al., 2013).

A final unresolved question is about the involvement of sensorimotor regions in the understanding of either symbolic gesture and words: to better understand the relation between gesture and speech and to propend for the integrated systems or the independent systems hypothesis, a specific analysis of the neural structures involved in the prior understanding of the single signals presented alone, beyond their subsequent or contemporary interaction, is necessary.

Chapter 4 – Study 1: Temporal characterization of behavioural integration between symbolic gestures and words

4.1 Introduction

The studies previously described in chapter 3 reported that when a symbolic gesture accompanies speech, it influences the voice spectra of the corresponding in meaning word and, conversely, the pronounced word affects the kinematics of the corresponding in meaning gesture (Bernardis and Gentilucci, 2006; Gentilucci et al., 2006). According to the authors, the two signals were also integrated in this case, because the social aspect of the word was emphasized by the gesture. In these studies (Bernardis and Gentilucci, 2006; Gentilucci et al., 2006), participants simultaneously produced or observed/listened the two signals (arm gesture or word). Thus, it is logical to suppose that the simultaneity favoured integration. Other studies (Vainiger et al., 2014; Fabbri Destro et al., 2014) presented gesture and word in succession and measured if lexical decision or semantic judgment on the word was facilitated or interfered by the presentation of a previous gesture. The gesture could be either related or unrelated to word meaning. These authors focused on the time of decision in a lexical-semantic task rather than on modification in characteristics of the gesture-word production (**integration**). On the basis of these data, the problem arises whether elaboration of the signal is always joined to integration with the other signal even when they are processed in succession and, in affirmative case, when this occurs.

4.2 Aims of the study

The study had the following aims:

1. To investigate if the behavioural **integration** between emblems and words existed even if the two signals were presented in succession.
2. To test if this mechanism was peculiar for gestures and words or it maintained equal features if the communicative signals were both verbal stimuli.
3. To investigate how **integration** was coupled with **lexical-semantic judgement**, clarifying if comprehension and integration are same or different processes and if the former is necessary for a primary conceptual elaboration of a communicative signal.
4. To test the effect of manipulation of the time of signals presentation in order to investigate the temporal features of the processes of **integration** (in what conditions and when it occurs) and **semantic comprehension**.

We addressed these problems in experiment 1 in which participants executed a lexical decision task on a word (target) which followed a meaningful or meaningless symbolic gesture (prime). The time of prime duration could be short (100 ms), intermediate (250 ms) or long (400ms), randomly. The lip kinematics (mean velocity of lip opening, MLV) and voice spectra (formant 1 and 2 of the first syllable of the target word, F1 and F2) were analyzed to search for integration effects, whereas time to response (TR) was used to search for gesture effects (facilitation or interference) on task response. The influence of the observed gesture on the pronounced word might be the consequence of the capability of the gesture to couple with word (Bernardis and Gentilucci, 2006; Gentilucci et al., 2006), or of a general process that integrates whatever signal (either gesture or word) with the other signal (either word or gesture). In other words, the capacity to influence speech could be either peculiar to gesture or common to both communicative signals. To answer to this question, experiment 2 aimed at discovering whether a prime word influenced a target word similarly to when the prime was a gesture (experiment 1). We did not present a prime word and a target gesture for the reason that the effects of prime gesture on target word voice spectra were difficult to compare with the effects of prime word on target gesture kinematics. In sum, taken together the results of experiments 1 and 2 aimed to clarify the qualitative and temporal features of behavioural integration process between gestures and words presented in succession; they also underlined similarities and differences in this process when, instead, a word preceded a word. Results described in study 1 were published on De Marco et al., (2015).

4.3 Materials and Methods

Participants

Two samples of twelve participants each (experiment 1: 6 males, mean age 23.4 ± 2.7 years, experiment 2: 9 males, mean age 26.6 ± 3.6 years) took part in two experiments. We preferred to conduct each experiment with a different cohort of participants in order to avoid reciprocal contamination between the tasks. The participants were right-handed (according to Edinburgh Handedness Inventory, Oldfield, 1971) and Italian native speakers. They had normal or corrected-to-normal vision and no history of neurological or psychiatric disorder. The Ethics Committee of the Medical Faculty at the University of Parma approved the study. The experiment was conducted according to the principles expressed by the Declaration of Helsinki. All the participants in the present study provided written informed consent.

Stimuli

The stimuli were primes and targets presented in succession. In experiment 1, the primes were the following: five pictures showing actor’s postures corresponding to different symbolic gestures, and five pictures showing actor’s postures representing meaningless gestures in which the arm was postured as in the corresponding meaningful gesture and only a part of the hand (frequently one finger) was postured differently of the corresponding meaningful gesture (Fig. 5). The targets were ten pictures showing the still actor with a strip on which one of five words congruent with the meaning of the gesture, or one of five words expressing an incongruent although related meaning was printed (Fig. 5, Table 1). In other five pictures, the actor presented pseudo-words in which one or two letters of the presented corresponding words were changed. Nevertheless, the pseudo-words could be easily read. In each picture the actor was facing the video-camera, and showed the gesture with the right hand without producing any facial expression. No audio was associated to picture presentation. Table 1 reports the presented meaningful gestures, and the corresponding congruent and incongruent words. The words were matched both in terms of length (expressed in number of characters) and frequency, evaluated by the COLFIS database (Laudanna et al., 1995). An unpaired two tailed t-test was used to compare the words relative to congruent and incongruent conditions. Both variables resulted to be largely not significant (mean length, number of letters: congruent 4, incongruent 3.6, $p = 0.221$; mean frequency: congruent 40.6, incongruent 5.4, $p = 0.621$).

In experiment 2 the stimuli were primes and targets presented in succession. The prime was one picture showing a still actor with a strip on which one of five meaningful words and pseudo-words was printed. In pseudo-words, one or two letters were different from those of the corresponding presented word. The targets were ten pictures showing the still actor with a strip on which one of five words congruent with the meaning of the prime, or one of five words expressing an opposite meaning was printed (Fig. 5, Table 1). Other five pictures presented pseudowords. Under no circumstances prime and target words exactly matched. An unpaired two tailed t-test was used to compare the target words relative to congruent and incongruent conditions. Both variables resulted not significant (mean length, number of letters: congruent 3.6, incongruent 3.2, $p = 0.66$; mean frequency: congruent 41.2, incongruent 6.6, $p = 0.32$). The same was observed for prime words (mean length = 4.6, comparisons with congruent and incongruent targets $p = 0.30$, $p = 0.13$, mean frequency = 4.4, comparisons with congruent and incongruent targets $p = 0.20$, $p = 0.37$).

Gesture	Congruent word	Incongruent word	N. of word letters congruent–incongruent	Word Frequency congruent–incongruent
Thumb up	Well (BENE)	Badly (MALE)	4–4	4–4
Thumb down	Badly (MALE)	Well (BENE)	4–4	7–4
Stop	Stop (FERMO)	Go (VAI)	5–3	132–1
Ok	Yes (SI)	No (NO)	2–2	49–10
Victory	Win (VINCI)	Lose (PERDI)	5–5	11–5

Table 1. Gestures and words (translated in English) presented in the study. In brackets the words in Italian.

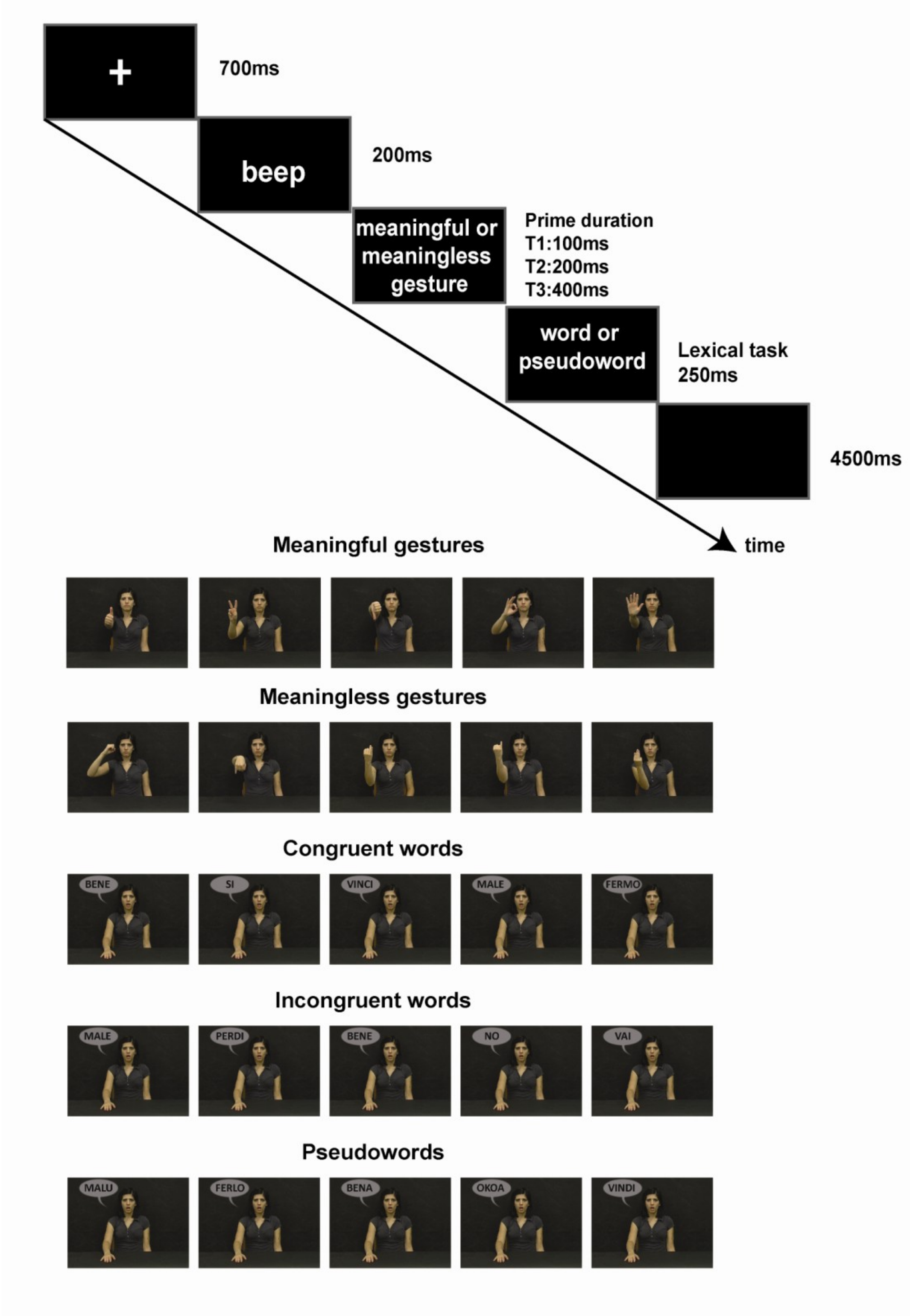


Figure 5*: Stimuli presented in experiments 1 and 2 and procedure used in experiment 1. The lower part shows pictures of meaningful, meaningless (primes) gestures (upper part) and congruent, incongruent (targets) words (lower part). The lowest row shows the pseudo-words used in the experiments. The upper part shows the procedure used in experiment 1.*

Procedure

Stimuli were presented on a PC display using a software developed using MATLAB version 7.7 (R2008b). The PC display was placed on a table plane at a distance of 60 cm from the body of the participant sitting in front of it. He/she performed a lexical go/no-go task during which a prime was presented after a cross (700 ms duration), and a BEEP (200 ms duration, in total 900 ms). The prime could last 100 ms, or 250 ms, or 400 ms followed by a blank panel (50 ms duration). Then, the actor and the strip were presented for 250 ms (Fig. 5). The prime could be a gesture (experiment 1) or a word (experiment 2) that could be either meaningful or meaningless. The target could be either a word or a pseudo-word printed on the strip. The experimental conditions were as follows (prime/target): meaningful-gesture/congruent-word, meaningful-gesture/ incongruent-word, meaningless-gesture/congruent-word, meaningless-gesture/incongruent-word, meaningful-gesture/pseudo-word. The two experiments were administered separately following the same procedure: each condition was presented twice (10 trials) for each prime duration (in total 30 trials for each couple prime-target). A baseline condition was run in which the target word alone (i.e. without the actor and strip) was presented twice in each block after the cross, the beep and a blank panel lasting 500 ms. The experimental sessions were divided in two blocks randomly presenting the same trials (75 trials plus 8 baseline trials for each block). The eight baseline trials were randomly presented at the beginning of the first block, and the same eight trials were randomly presented at the end of the second block. The participant was required to discriminate whether the target was either a word or pseudoword and to pronounce aloud only the word.

Lip movement, voice recording and data analysis

The lip kinematics during word pronunciation was recorded using the 3D-optoelectronic SMART system (BTS Bioengineering, Milano, Italy). This system consists of six video cameras detecting infrared reflecting markers (spheres of 5-mm diameter) at a sampling rate of 120 Hz. Spatial resolution of the system is 0.3 mm. The infrared reflective markers were attached to the participant’s upper and lower lip. The data of the recorded movements were analysed using home-made scripts developed using MATLAB version 7.7 (R2008b). Recorded data were filtered using a Gaussian low pass smoothing filter (sigma value, 0.93). The time course of lip opening and closing was visually inspected: the beginning of the movement was considered to be the first frame in which the distance between the two markers placed on the lips increased and decreased more than 0.3 mm (spatial resolution of the recording system, i.e. minimal displacement greater than noise that the system is able to record) with respect to the previous frame. The end of the movement was the first frame in which the distance between the two lips increased/decreased less than 0.3 mm with respect to the previous frame. We measured for successive statistical analysis MLV (Mean Lip Velocity), calculated as ratio between maximal lip aperture and time to maximal lip aperture. The participants wore a light-weight dynamic headset microphone (Shure, model WH20). The frequency response of the microphone was 50–15,000 Hz. The microphone was connected to a PC by a sound card (16 PCI Sound Blaster; CREATIVE Technology Ltd., Singapore). We acquired participants' voice data of the pronounced first syllable of the word using the Avisoft SAS Lab professional software (Avisoft Bioacoustics, Germany), and calculated the participants' voice parameters using the PRAAT software (www.praat.org). Specifically, we analyzed the time course of formant (F) 1 and 2. It is well known that F1 and F2 univocally define vowels from an acoustical point of view (Leoni and Maturi, 2002). Both formant transition and pure vowel pronunciation were measured and averaged. We also calculated TR (Time to Response), that is the time elapsed from BEEP beginning and beginning of the analysed vowel pronunciation.

Repeated measures ANOVAs were carried out on F1, F2, MLV, and TR. Analyses were separately conducted on data of experiments 1 and 2. The reason was to avoid contamination between word and gesture prime effect. The same reason can explain why we preferred to conduct the experiments on different samples of participants.

The within subjects factors were **prime** (gesture or word, meaningful vs. meaningless), **congruence** (congruence vs. incongruence) and **time** (duration of prime gesture: T1, 100 ms, vs. T2, 250 ms, vs. T3, 400 ms). Moreover, concerning F1, and MLV in T2 condition and TR in T1, T2, and T3, we also performed the same comparisons after normalizing data with respect to baseline. In all analyses, post-hoc comparisons were performed using the

Newman-Keuls procedure. The significance level was fixed at $p = 0.05$. Sphericity of the data was verified before performing statistical analysis (Mauchly's test, $p > 0.05$). All variables were normally distributed as verified by Kolmogorov-Smirnov Test ($p > 0.05$). η^2partial was also calculated.

4.4 Results

Voice spectra

Experiment 1

ANOVAs on F1 revealed significance for the interaction between gesture, congruence and time ($F(2,22) = 3.6$ $p = 0.046$, η^2partial = 0.24, Fig. 6). In the ANOVAs separately conducted for every time, the duration of 250 ms (T2) produced an increase in F1 when the meaningful gesture (prime) was congruent with the word (target) as compared to the congruent meaningless gesture ($F(1,11) = 5.0$, $p = 0.05$, η^2partial = 0.30, post-hoc, $p = 0.042$, Fig. 6). In contrast, the same comparison was not significant at T1 ($F(1,11) = 0.1$, $p = 0.79$) and T3 ($F(1,11) = 1.7$, $p = 0.22$). Concerning T2, F1 normalized with respect to baseline showed a significant interaction between gesture and congruence ($F(1,11) = 4.9$, $p = 0.05$, η^2partial = 0.26). F1 in response to congruent meaningful gesture increased in the comparison with all the other conditions (i.e. $p = 0.04$, meaningless congruent, $p = 0.04$, meaningful incongruent, $p = 0.05$, meaningless incongruent, Fig. 6).
The analysis of F2 revealed neither significance for factor (except congruence see below) nor for interactions between factors.

Experiment 2

ANOVAs on F1 of target word revealed that the interaction between prime word and congruence was significant ($F(1,11) = 4.8$ $p = 0.05$, η^2partial = 0.27, Fig. 7). F1 of meaningful congruent word was higher than F1 of meaningless congruent word (post-hoc =0.045, 569Hz vs. 565Hz), independently of prime duration. In a second ANOVA, we compared F1 normalized with respect to baseline in the condition of meaningful and meaningless prime. The interaction between prime and congruence was significant ($F(1,11) = 4.9$, $p = 0.05$, η^2partial = 0.3, Fig. 7). All comparisons were significant ($p < 0.03$) except that between meaningful and meaningless incongruent prime ($p = 0.6$). Specifically,

F1 related to meaningful congruent prime word was greater than F1 related to meaningless congruent prime word. The values of F1 related to incongruent meaningful and meaningless prime word were −2.36% and −2.21%. They were both significantly different from zero ($t(36) = -3.87$, $p = 0.00045$; $t(36) = -3.45$, $p = 0.0014$). The analysis on F2 revealed significance neither for factors nor interactions between factors.
In experiment 2, the meaningful prime word congruent with target word induced an increase in F1 as compared with congruent meaningless prime and this result was valid for whatever prime duration. In contrast, meaningful and meaningless prime word incongruent with target word induced a decrease in F1 when compared with baseline. In other words, the congruence induced a double effect on F1: enhancement and interference for congruent and incongruent prime word, respectively.

Lip kinematics

Experiment 1

MLV was affected by gesture prime ($F(1,11) = 9.4$, $p = 0.01$, η2partial = 0.46, meaningful = 207 mm/s, meaningless = 197 mm/s) and time ($F(2,22) = 3.3$, $p = 0.05$, η2partial = 0.23, T1 = 192 mm/s, T2 = 202 mm/s, T3 = 212 mm/s; post hoc test, T3 vs. T1 $p = 0.04$). In order to compare these results with the results found for F1 we conducted ANOVAs separately for every time; the interaction between congruence and gesture was significant in T2 condition only ($F(1,11) = 7.6$, $p = 0.01$, η2partial = 0.4). Fig. 6 shows that in the case of congruence, when the gesture was meaningful, MLV was greater than when gesture was meaningless (post hoc $p = 0.001$). In contrast, no significance was found when the gesture was incongruent (post hoc $p = 0.65$). MLV normalized with respect to baseline showed a significant interaction at T2 between congruence and gesture ($F(1,11) = 8.9$, $p = 0.012$, η2partial = 0.45): meaningful and congruent gesture made MLV higher than in all the other conditions ($p = 0.002$, $p = 0.003$, $p = 0.002$, Fig. 6). Normalized MLV was significantly different from zero in the condition of congruent meaningful gesture. ($t(11) = 2.37$, $p = 0.037$).
Note that factor congruence was significant in all the reported analyses. This was consequent to the fact that the words were different between congruent

and incongruent conditions independently of prime. Consequently, they produced different kinematic and vocal parameters. So, normalization with respect baseline was necessary in order to distinguish prime effects from word effects. The prime effect should induce variation in normalized parameters. In contrast, word effect should affect not-normalized parameters.

Experiment 2.

Neither factor nor interaction between factors affected raw and normalized MLV data. In particular, the interaction between prime and congruence was not significant (raw data, $F(1,11) = 0.01$, $p = 0.91$; normalized data, $F(1,11) = 0.361$, $p = 0.56$, Fig. 7).

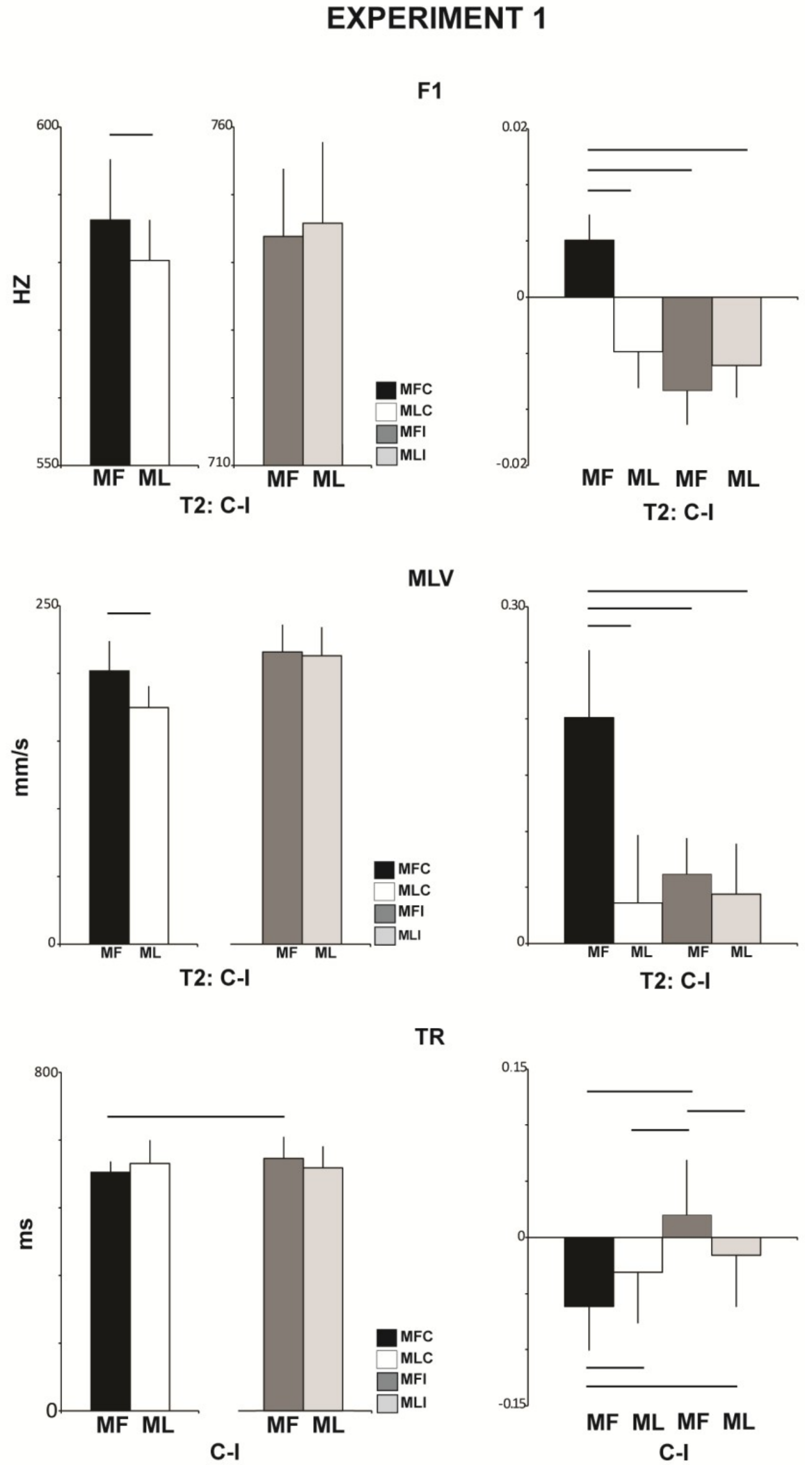


Figure 6. *Effects of gesture prime on vocal parameters (Formant 1, F1), lip kinematics (MLV, mean lip velocity), and time to response (TR) in experiment 1. F1 was the mean of values recorded during pronunciation of the first vowel of the target word. MLV was the mean lip velocity during the initial lip opening. MF: Meaningful Gesture, ML: Meaningless Gesture, C: congruent, I: Incongruent, T2: Gesture Duration of 250 ms. Vertical and horizontal bars represent SE and significance in the statistical comparisons, respectively. Adapted from De Marco et al. (2015).*

TR

Experiment 1

ANOVA on TR revealed (1) that factor time was significant ($F(2,22) = 29.8$ $p = 0.0001$ $\eta2partial = 0.73$) as well (2) interaction between gesture and congruence ($F(1,11) = 10.78$ $p = 0.012$ $\eta2partial = 0.49$). (1) TR was greater at T1 (622 ms) than T2 (565 ms, $p = 0.0001$) and T3 (554 ms, $p = 0.0001$, Fig. 6). There was no significant difference between T2 and T3 ($p = 0.24$). (2) When the prime was a meaningful gesture, TR was shorter in the condition of congruence compared to incongruence (post hoc $p = 0.021$, Fig. 6).

The comparison between meaningful and meaningless TRs normalized with respect to baseline, revealed that the interaction between prime and congruence was significant ($F(1,11) = 10.68$ $p = 0.007$, $\eta2partial = 0.5$). In post hoc test, comparisons were all significant ($p < 0.05$) except that between meaningless congruent and incongruent gestures ($p = 0.3$). Mean normalized TR in the condition of congruent meaningful prime was -6.17%. It was significantly different from zero (t test, $t(35) = -2.172$, $p = 0.037$).

Experiment 2

In the first ANOVA the interaction between prime, congruence, and prime duration was significant ($F(2,22) = 3.5$, $p = 0.05$, $\eta2partial = 0.21$). When the meaningful prime was presented for 400 ms (T3), TRs related to meaningful prime were longer in the comparison with meaningless prime, only in condition of congruence (post-hoc $p = 0.014$, 491 ms vs. 464 ms, Fig. 7). No difference was found in the incongruent condition (post-hoc $p = 0.9$). Then, concerning normalized TR, we compared meaningful with meaningless condition. The factors were prime (meaningful vs. meaningless), congruence (congruence vs. incongruence), and prime duration (T1 vs. T2 vs. T3). The interaction between prime, congruence and prime duration was significant ($F(2,22) = 3.6$, $p = 0.044$, $\eta2partial = 0.3$). There was less decrease at 400 ms in the condition of congruent and meaningful prime in the comparison with congruent and meaningless prime ($p = 0.024$), but not in incongruent condition ($p = 0.9$, Fig. 7). Mean values of normalized TR in the conditions of meaningful and meaningless congruent and incongruent prime were −8.45%, −12.73%,

−13.5%, −12.4% respectively. These values were all significantly different from zero ($t(11) = -2.5$, $p = 0.05$, $t(11) = -3.8$, $p = 0.0028$, $t(11) = -3.4$, $p = 0.006$, $t(11) = -5.2$, $p = 0.0003$).
Accuracy in experiment 1 and 2 was 99.7% and 99.1%, respectively. Thus, the effects on TR cannot be explained in terms of speed-accuracy trade-off.

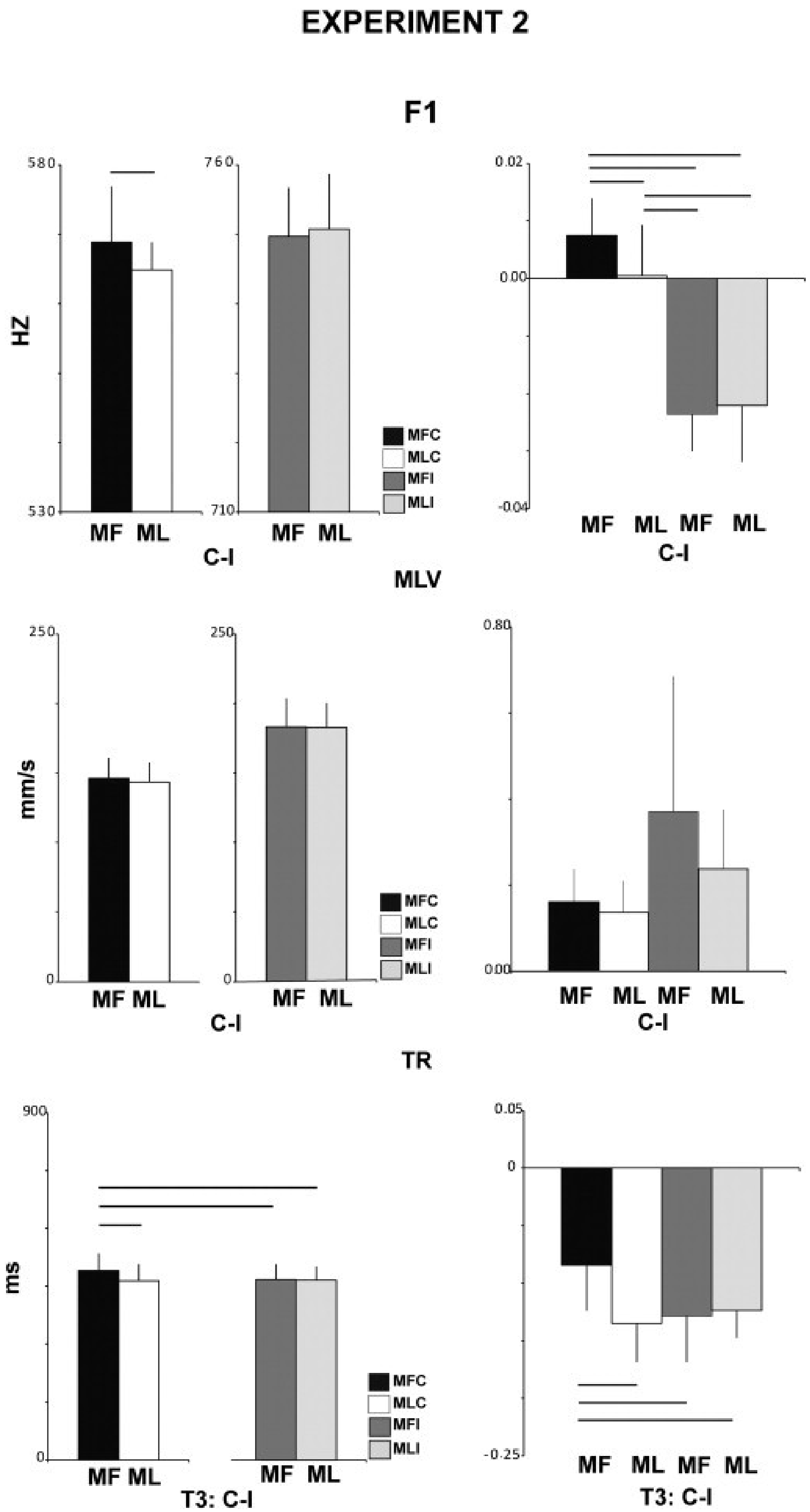


Figure 7. *Effects of word prime on vocal parameters (F1), lip kinematics (MLV, mean lip velocity), and time to response (TR) of target word in experiment 2. T3: Prime Duration of 400 ms. Other conventions as in Fig. 6. Adapted from De Marco et al. (2015).*

4.5 Preliminary Discussion (experiments 1 and 2)

In previous studies (Barbieri et al., 2009; Bernardis and Gentilucci, 2006; Gentilucci et al., 2006) using tasks in which gestures and words were produced at the same time, the two signals were reciprocally integrated when they were both meaningful and congruent. That is, the gesture affected voice spectra of words and, conversely, the word affected the gesture kinematics. The data of experiments 1 and 2 showed that integration occurred even when they were presented in succession, the prime being a symbolic gesture or word and the target being a congruent or incongruent word. However, SOA (Stimulus Onset Asynchrony) was a critical factor, but only for experiment 1. When the time of prime presentation was short (100 ms) or long (400 ms), integration was not noticed (i.e. the meaningful gesture was not related to any variation in F1 and MLV). In contrast, when the time of presentation was 250 ms (intermediate prime duration), the gesture was integrated with word (and the result was an increase in F1 and MLV when the gesture was meaningful and congruent). In experiment 2, integration was, in contrast, independent of prime duration.

The data of experiments 1 and 2 seem to differ from those by Gentilucci and colleagues (Barbieri et al., 2009; Bernardis and Gentilucci, 2006; Gentilucci et al., 2006). These authors found that integration resulted in an increase in F2 rather than F1. However, in these previous studies, the gestures were moving stimuli, the words were acoustically presented and participants performed a naming task rather than a lexical task. Mainly, the signals were characterized by greater communicative content in comparison with the signals in experiments 1 and 2. The naming task made pregnant the communicative content and this could be responsible for the increase in F2 (Bernardis and Gentilucci, 2006; Gentilucci et al., 2006). Conversely, the lexical task in the present experiment did not induce magnification of the communicative content of the gesture but could induce integration between syllables and magnification of the voice and kinematic parameters. That is, when the gesture was meaningful and congruent, pronunciation of the word corresponding to gesture added to pronunciation of the target word increasing mouth opening (i.e. MLV and F1, Leoni and Maturi, 2002).

No prime effect was observed on MLV in experiment 2. The pronunciation of the vowel in a word is related mainly to changes in internal mouth posture and consequently, it is logical to suppose that word prime mainly affected F1 of word target rather than lip movements. The involvement of lips movements in experiment 1 may be consequent to greater activation of the motor system since the gesture was probably verbalized and translated in a mouth motor program.

In experiment 1, meaningful congruent gesture produced a decrease in TRs. This result is in agreement with Vainiger et al. (2014) who found facilitation in a lexical decision task and interference in a semantic relatedness judgment task.

In experiment 2 the congruent meaningful prime affected TR: lexical decision and consequent word pronunciation were delayed when a meaningful congruent prime preceded the target word by 400 ms. It may be that, when the interval between the onsets of prime and target increased, more time was spent in a deeper probably controlled analysis (Neely, 1977, 1991; Posner and Snyder, 1975).

Chapter 5 - Study 2: Gesture and words: do they make use of motor simulation?

5.1 Introduction

Another problem related to the nature of processing of communication signals (both symbolic gesture and word) is whether they make use of motor simulation in order to comprehend their meaning and how comprehension is related to integration. Although some studies reported evidence of activation of premotor circuits in response to symbolic gestures (Villareal et al., 2008; Willelms et al., 2009; Andric et al., 2013), it remains not clear if also symbolic gestures required motor simulation to be understood, as transitive actions and pantomimes do (Buccino et al., 2004, 2001; Fadiga et al., 1995; Gangitano et al., 2001; Rizzolatti et al., 2014). In a recent single pulse TMS study, Campione et al., (2014) failed to find a modulation of MEP activity, after presentation of symbolic gestures, due to TMS applied to primary motor cortex (M1), compared to a silent and still actor. A possible explanation of this result is that an automatic simulation of the signal activated learned motor representations for an access to semantics, but the activation was more praecox than the time used by the authors.

5.2 Aims of the study

The study had the following aims:

1. To define if symbolic gestures made use of motor simulation to comprehend the concept semantics.
2. To demonstrate if also words related to gestures made use of motor simulation, clarifying if both signals were initially processed by the same system.
3. To define the exact timing of the eventual motor activation in response to communicative stimuli and if this activation corresponded to covert understanding of semantics.
4. To clarify how this process could be temporally coupled with behavioural integration of gestures with words and words with words.

Experiments 3 and 4 aimed at determining whether an early motor simulation was performed after gesture or word prime presentation. We used the same stimuli and a task similar to experiments 1 and 2, in order to compare TMS results with behavioural results. We presented a prime gesture (experiment 3) or a prime word (experiment 4) followed by a target word congruent or incongruent with the gesture or word. The prime duration was 150, 300, and 550 ms. We applied TMS to hand M1 100, 250 and 500 ms post-stimulus, that is 50 ms before the gesture turned off. We selected to stimulate 500 rather than 400 ms post-stimulus in order to compare the results with those by Papeo et al. (2009) who found motor inhibition when presenting action words at that delay. If stimulation is effective 100 ms post-stimulus we can hypothesize that motor simulation is used to understand gesture and word meaning. Mainly, we were interested in comparing the temporal relation between comprehension and integration in order to establish whether comprehension is necessary for integration or, vice versa, integration is necessary for comprehension. Results described in study 2 were published on De Marco et al., (2015).

5.3 Materials and Methods

Participants

Two samples of twelve participants each experiment 3: 9 females, mean age 27.5 ± 3.7 years and experiment 4: 9 females, mean age of 26.6 ± 3.6 years) took part in two experiments. As for study 1, the participants were right-handed (according to Edinburgh Handedness Inventory, Oldfield, 1971) and Italian native speakers. They had normal or corrected-to-normal vision and no history of neurological or psychiatric disorder. The Ethics Committee of the Medical Faculty at the University of Parma approved the study. The study was conducted according to the principles expressed by the Declaration of Helsinki. All the participants in the present study provided written informed consent. All the participants were checked for contraindications to the use of Transcranial Magnetic Stimulation (Wasserman et al., 1998; Rossi et al., 2009).

Stimuli

The stimuli were the same used for experiment 1 in the case of experiment 3 (meaningful/meaningless gestures as prime and words/pseudo-words as target, see methods of Study 1, Fig. 5 and Table 1) and the same used for experiment 2 in the case of experiment 4 (words/pseudo-words both used as prime or targets).

Procedure

The TMS experiments took place in a soundproofed room where participants seated on a comfortable armchair, with their elbow flexed at 90° and their hands prone in a relaxed position. We used a chin rest to keep the subject's head still. In experiments 3 and 4 the stimuli were the same as in experiments 1 and 2, respectively. Stimuli were presented on a PC display (19 inches) placed on a table at a distance of 60 cm from the participant. The experimental procedure was programmed using Matlab software (MATLAB version 7.7, R2008b; Psychophysics Toolbox extensions, Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) to control stimuli presentation and to deliver TMS pulses. The two experiments were administered separately following the same procedure: pictures of an actor, randomly showing one of five symbolic gestures (or words) and five meaningless gestures (or words) used in the behavioural experiment 1 (or 2), were presented after a fixation cross (700 ms, Fig. 5). The duration of each prime presentation was 150, 300 or 550 ms. In each trial, a single TMS pulse was delivered at 100, 250 and 500 ms after prime onset (TMS delay). Meaningful and meaningless stimuli were presented 15 times for each TMS delay (in total 120 stimuli: 60 meaningful gestures and 60 meaningless gestures). Like in experiments 1 and 2, after turning off of each meaningful/meaningless gesture or word, a picture with the still actor with a strip showing a word (congruent or incongruent with the meaning of the gesture (or word) or a pseudoword was presented). Presentation lasted 250 ms (Fig. 5). Fifteen baseline trials (5 for each TMS delay) were run at the beginning and at the end of the TMS session (in total 30 trials). The baseline trials were constituted by a picture of the actor with his arm and hand in rest position showing no gesture (the hands were not visible because placed under the table plane) and without a strip. In addition, 30 trials, in which a meaningful prime was followed by a pseudo-word, were included in the paradigm but not analyzed. Pseudo-word inclusion allowed the participants to make a lexical decision on words/pseudo-words. Specifically, in 30% of the trials, a question mark appeared after presentation of words/pseudo-words and lasted 2000 ms. Subjects were instructed to pay attention to the prime and then to words/pseudo-words. Participants decided whether the word/pseudoword had sense or not. They pronounced aloud “s” (sense) or “n” (non sense) in response to the word and pseudo-word, respectively. Trials with incorrect responses and no responses were discarded for successive analyses. After 2000 ms, a new trial was run. At the beginning of the session, the experimenter explained the task and provided examples of gestures and words similar but not equal to those used in the experiment.

Transcranial magnetic stimulation (TMS), electromyography recording (motor evoked potentials, MEPs) and data analysis (experiments 3 and 4)

A single-pulse TMS was delivered to M1. MEPs induced by TMS were recorded from the right first dorsal interosseus (FDI) and abductor digiti minimi (ADM) muscles in experiments 3 and 4, and from right FDI in experiment 4. Continuous EMG recordings from FDI and ADM were acquired with a CED Micro 1401 (Cambridge Electronic Design, Cambridge, U.K.) connected to CED 1902 amplifier and interfaced with CED Spike software. EMG signals were amplified (1000×), band-pass filtered (20–2000 Hz) and digitized at a sampling rate of 5 kHz. Pairs of surface electrodes (Ag–AgCl, disposable, 7 mm × 4 mm) were attached, one to the belly of the right FDI and ADM muscles (active electrode) and one to the skin overlying the second metacarpophalangeal joint (reference electrode). The ground electrode was placed on the left wrist. Visualization and later processing of the EMG signal was done using Spike2 software (CED Ltd.). A figure-of-8 coil (Magstim Co. Ltd.) connected to a Bistim system (Magstim Co. Ltd.) was placed over the left M1. The intersection of the coil was placed tangentially to the scalp with the handle pointing backward and laterally at a 45°angle away from the midline. By using a slightly suprathreshold stimulus intensity, the coil was moved to determine the optimal position from which maximal amplitude MEPs were elicited in the controlateral FDI muscle. The optimal position was then marked on the scalp to ensure correct coil placement throughout the experiment. The intensity of magnetic pulses was set at 120% of the resting motor threshold (rMT), defined as the minimal intensity of the stimulator output that produces MEPs with amplitude of at least 50 μV in the higher threshold muscle with 50% probability (Rossi et al., 2009). In this way, a stable signal could be recorded from both muscles. The absence of voluntary contraction was continuously verified visually throughout the experiment. When muscle tension was detected, participants were invited to relax and in the off-line MEP analysis, trials with muscle contractions not related to TMS were discarded.

As for behavioural experiments (study 1), analyses were separately conducted on data of experiment 3 and 4. Individual MEPs of FDI and ADM muscles were visually inspected and rejected if they were contaminated by contraction not due to stimulation (1.5 % out of the total trials). The peak-to-peak amplitude (mV) of each MEP was computed by using MATLAB software (MATLAB version 7.7, R2008b). MEP amplitudes less than 50 μV were not considered (8.4 % out of the total trials). Normalized MEPs were calculated as variation of each value with respect to the mean of the baseline values. Mean values were submitted to repeated-measures ANOVAs with **prime** (meaningful vs. meaningless) and **stimulation delay** (T1, 100 ms vs. T2, 250 ms vs. T3, 500 ms) as within-subjects factors. All post hoc comparisons were carried out using Newman–Keuls test. Significance was established in all analyses at $p = 0.05$. MEPs amplitudes deviating more than 3 standard deviations from the mean for each condition were excluded as outliers (<3%). Sphericity of the data was verified prior to performing statistical analysis (Mauchly's test, $p > 0.05$). All variables were normally distributed as verified performing Kolmogorov-Smirnov Test ($p > 0.05$). η2partial was also calculated.

5.4 Results

The participants were able to recognize whether the presented stimuli were either words or pseudo-words. Indeed, the mean percentage of correct responses was 97.5% and 87.4% in experiments 3 and 4 respectively.

Experiment 3

Analysis of the not-normalized data.

There was no significant difference among the raw MEP amplitudes recorded from the ADM during the observation of the baseline, meaningless and meaningful gestures ($F(2,22) = 1.6$, $p = 0.2$). Raw mean MEP amplitudes of FDI muscle of baseline trials administered at the beginning and the end of the experimental session were not significantly different from each other ($F(2, 20) = 1.49$, $p = 0.25$).

Analysis of the normalized FDI MEPs.

To test the effects of meaning as compared with no-meaning, raw data for each participant were normalized, transforming mean FDI MEPs of both meaningful and meaningless gestures into percentages with respect to mean MEPs of corresponding baseline stimuli. A repeated measures ANOVA was performed on normalized MEP values, using gesture (meaningless vs. meaningful) and stimulation delay (T1 vs. T2 vs. T3) as within subjects factors.
The interaction between gesture and stimulation delay was significant ($F(2, 22) = 5.392$, $p = 0.012$, η2partial = 0.33, Fig. 8). Normalized MEP amplitude at T1 was greater for meaningful than for meaningless gestures (post hoc, $p = 0.01$; 53.8% and 34.6% respectively). Furthermore, concerning meaningful gestures, normalized MEP amplitude was greater at T1 than T2 and T3 (T1 = 53.8%, T2 = 20.6% and T3 = 12.29%, post hoc, T1 vs. T2 $p = 0.01$, T1 vs. T3, $p = 0.01$, T2 vs. T3, $p = 0.23$). No difference was found between meaningless gestures (T1 = 34.61%, T2 = 23.9% , T3 = 23.51% , T1 vs. T2, $p = 0.13$, T1 vs. T3, $p = 0.25$, T2 vs. T3, $p = 0.95$). Summing up, there was an increment in MEPs when a gesture (meaningful and meaningless) was presented. Indeed, normalized data were significantly positive for both meaningless and meaningful gestures at T1 (t test: $t = 2.33$ $p = 0.038$, $t = 2.86$ $p = 0.014$) and for meaningless gestures at T3 ($t = 2.63$, $p = 0.022$). This result may depend on the fact that the picture of the actor showing a posture (meaningless or meaningful) automatically activated a simulation of the movement in order to reproduce that gesture. However, increment in MEPs was significantly greater for meaningful than meaningless gestures. Since a still actor was presented and in motor terms the

complexity of the meaningful and meaningless movement in order to assume that posture did not vary (see methods of Study 1, Fig. 5), it is plausible to suppose that posture meaning was responsible for the TMS effect.

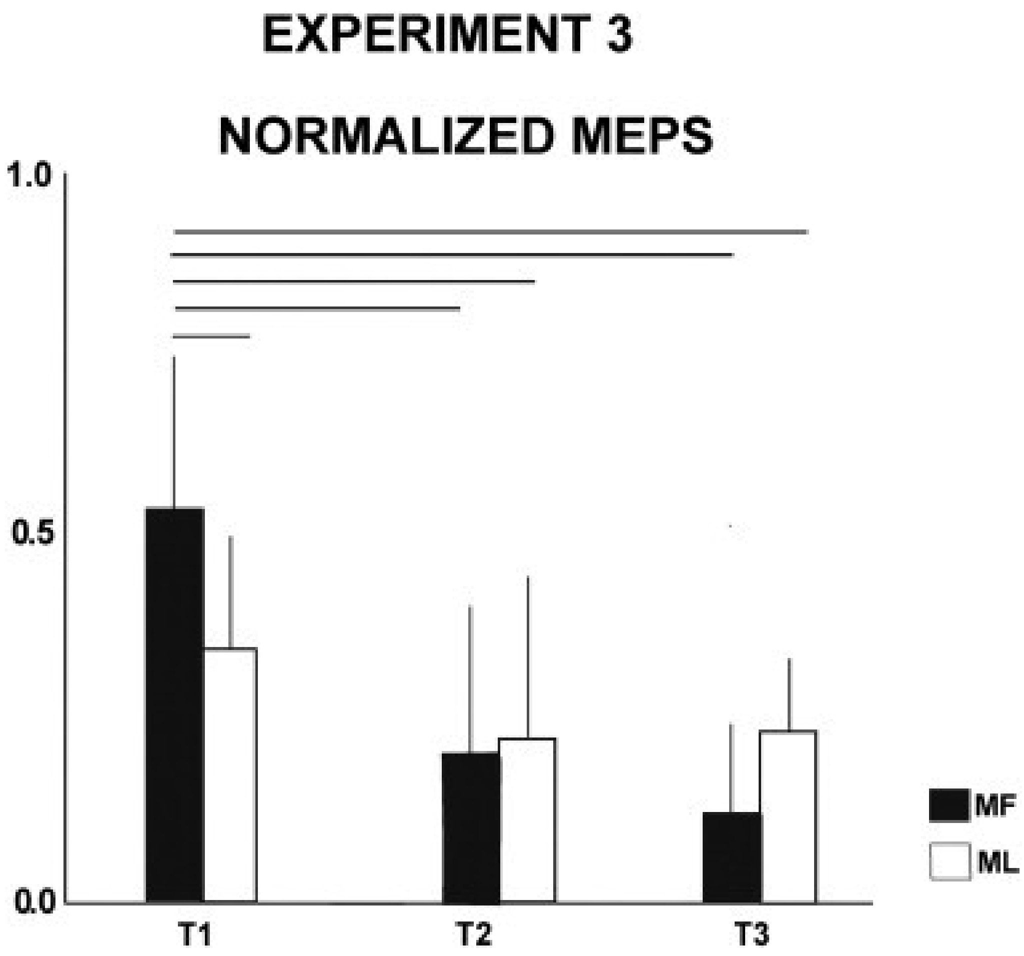


Figure. 8. *Motor Evoked Potentials (MEPs) of FDI muscle recorded in experiment 3 after single pulse Transcranial Magnetic Stimulation (TMS) of primary motor area during presentation of prime gesture; they are normalized with respect to baseline condition. MF: Meaningful Gesture, ML: Meaningless Gesture, T1: gesture duration of 150 ms, T2: gesture duration of 300 ms, T3: gesture duration of 550 ms. Other conventions as in Fig. 6. Adapted from De Marco et al. (2015).*

A further control ANOVA was performed with type of gesture as within factor. The factors were item (symbolic gesture: “thumb up” vs. “thumb down” vs. “OK” vs. “stop” vs. “win”) and time (T1 vs. T2 vs. T3). Factor symbolic gesture and interaction between symbolic gesture and time were not significant (F(4,44) = 2.14, p = 0,09, F(8,88) = 0.3, p = 0,96). Thus, it is plausible to suppose that there was no difference between the types of symbolic gestures in activating motor simulation.

Experiment 4

Analysis of the not normalized MEPs

Raw mean MEP amplitudes of FDI muscle in baseline trials administered at the beginning and the end of the experimental session were not significantly different from each other (F(2, 22) = 2.04, p = 0.12).

Analysis of the normalized MEPs.

The effect of meaning as compared with no-meaning was tested, by performing a repeated measures ANOVA on normalized MEP values, using prime word (meaningless vs. meaningful) and stimulation delay (T1 vs. T2 vs. T3) as within subjects factors. The interaction between prime and stimulation delay was not significant (F(2, 22) = 2.22, p = 0.13, Fig. 9). There was an increment in MEPs when a gesture (meaningful or meaningless) was presented. Indeed, normalized data were significantly positive for both meaningless prime words except at T3 (t tests in T1, T2, and T3 conditions: t = 3.8 p = 0.003, t = 2.2 p = 0.05, t = 1.41 p = 0.146) and meaningful prime words (t tests: t = 3.0 p = 0.001, t = 2.4 p = 0.03, t = 2.5 p = 0.02). These results may depend on the fact that the picture of the actor presenting a prime word (meaningless or meaningful) was a more complex stimulus in motor terms than a “silent” actor. This could cause an unspecific increment in MEPs.

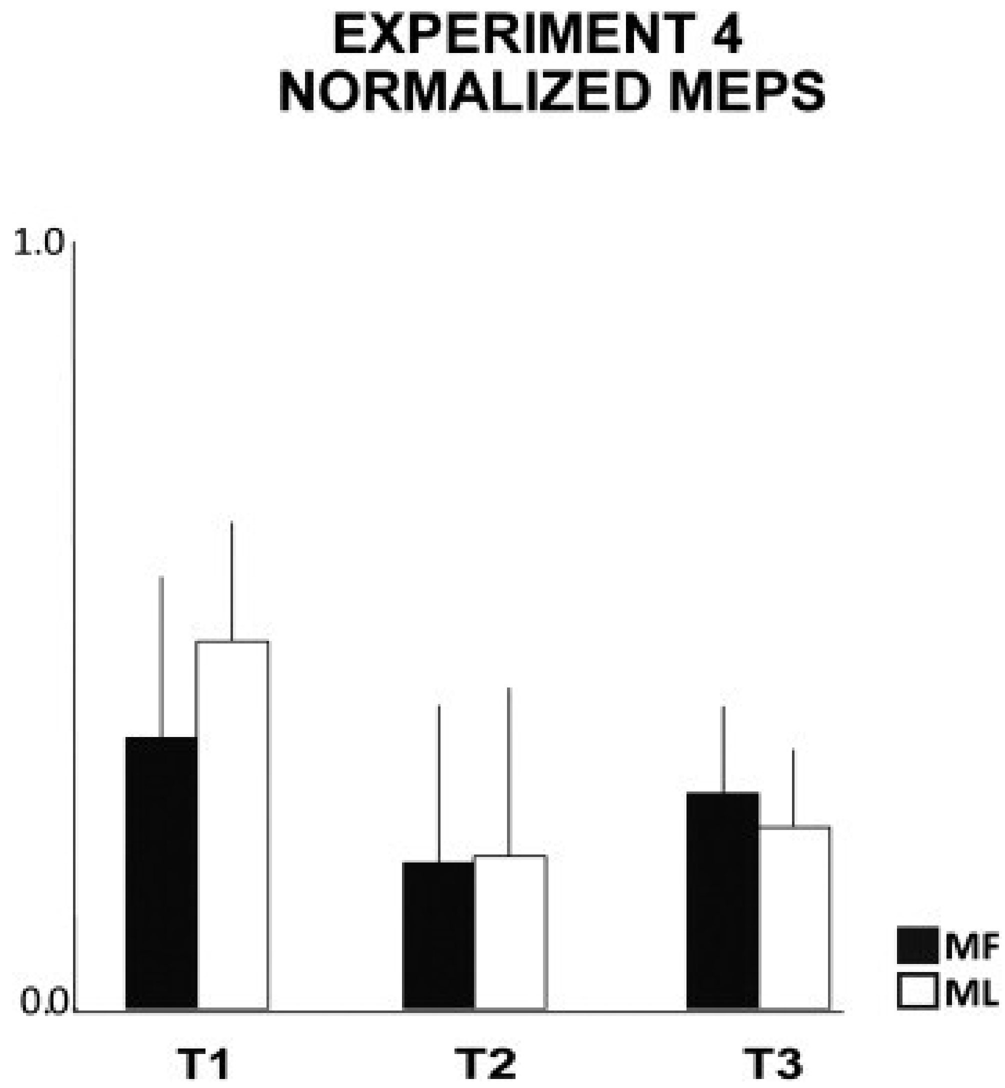


Figure 9. *Motor Evoked Potentials (MEPs) of FDI muscle recorded in experiment 4 after single pulse TMS of primary motor area during presentation of prime word; they are normalized with respect to baseline condition. Other conventions as in Fig. 6. Adapted from De Marco et al. (2015).*

5.4 Preliminary discussion

The results of experiment 3 support the hypothesis that even the presentation of symbolic gesture automatically activated a process of motor simulation. This process was active 100 ms post stimulus, and it might be used to automatically comprehend gesture meaning. Nevertheless, comprehension facilitated the lexical task when the gesture was meaningful and congruent with the word (see experiment 1). Differently from intransitive (symbolic) gestures, there are a lot of experiments showing that observation of transitive actions modifies motor cortex excitability. However, the time when it occurs is uncertain. In behavioural and TMS studies, Gangitano et al. (2001) proposed the moment of maximal finger aperture. De Stefani et al. (2013) proposed the final finger closing phase. In fact, both of them propose a moment of maximal motor activity, the one when the grasp aim was evident. Our data differs from those of previous experiments (De Stefani et al., 2013; Gangitano et al., 2001) for two reasons. The first is that intransitive gestures were presented, i.e. actions not directed towards target objects, but internally generated. The second is that the stimulus was still, i.e. an arm-hand posture assumed by the actor expressing a meaning. Nevertheless, it activated the motor cortex.

Symbolic gestures probably derive from idiosyncratic gestures that assumed a meaning after a process of conventionalization among individuals taking part in a certain culture (Burling, 1999). Thus, whereas transitive gestures are learned with experience of motor interactions with the external world during childhood, the symbolic ones are probably learned with experience of reciprocal communication with other individuals. Thus, in a certain sense, symbolic gestures may be closer to verbal language and farther from motor control in the comparison with transitive gestures. This is in accordance with Villarreal et al. (2008) who, in an fMRI experiment, found greater activation of IFG (Inferior Frontal Gyrus) for symbolic rather than transitive gestures. However, another fMRI study (Andric et al., 2013) showed a common activation of premotor cortex for both transitive and symbolic gestures.

We found greater motor activation for meaningful (symbolic) than meaningless gestures. This result is in accordance with the results of the fMRI study by Ferri et al. (2014) who found a larger involvement of left premotor cortex for the observation of symbolic than meaningless gestures. In contrast with these results, Campione et al. (2014) in a TMS study did not find any motor activation after presentation of meaningful gestures. A possible explanation may be that our stimulation was earlier (100 ms post-stimulus), whereas that in Campione et al.' study (2014) was late (250 ms post-stimulus), when probably gesture meaning was already acquired.

In experiment 4, we did not find any motor simulation after presentation of prime words. We cannot exclude that more literal words that describe gesture movement (e.g. “thumb up” or “thumb down” instead of “well” or “badly”, Table 1) could induce motor simulation. However, we were interested in a more general meaning of the word rather than a simple motor description of the gesture. In other words we aimed at determining, for example, whether the word “well” activated the motor representation “thumb up”.

Chapter 6 – Study 3: Embodied interaction between emblems and words: the role of motor context

6.1 Introduction

The results of study 2 suggest that while symbolic gestures are understood by means of embodied simulation like transitive actions, related words do not, and probably their semantic comprehension preferentially involves associative areas related to semantics and linguistic integration (Lau et al., 2008; Fabbri Destro et al., 2014). Summing up the results of studies 1 and 2, despite gesture and words shared the same process of integration, suggesting the existence of a same control mechanism (Gentilucci & Corballis, 2006), they seem to be initially processed by different systems, a modal motor system for gestures and an amodal system for words. When gesture is transformed from a modal representation to an amodal one, it can interact and be integrated with semantic related words. This is true at least for abstract/symbolic communicative words. Indeed, different studies that found activation of motor areas during action-words processing, did not report similar activation for abstract words (Dalla Volta et al., 2014; Innocenti et al., 2013).

However, some authors proposed that if abstract words were inserted in a “concrete context” or are preceded by concrete words they could involved motor system during semantic processing (Sakreida et al., 2013; Boulenger et al., 2009; Scorolli et al., 2011).

With this study, we tried to verify if the same premises could be applied to gestures and words. It is possible that the absence of gestural context in experiment 4 of study 2 caused the missing motor activation. Indeed, the words used in experiment 4 were strictly related to the gestures presented in experiment 3 but could result not specifically related to a posture without a specific constrain. Furthermore, although the link between a transitive action and the corresponding words is quite univocal (e.g., the action of grasping is linked to the verb “to grasp”) this is not true for symbolic gesture (e.g., the posture “Thumbs down” could refer to the adjective “bad” or “incorrect” but also to the abstract verb “to disapprove”). In addition, it is not clear what could happen if instead of a word related to the meaning of the gestures, a literal description of the movement is presented (e.g., literally the word “thumbs down”).

6.2 Aim of the study

The study had the following aims:

1. To investigate if the understanding of a symbolic word made use of motor simulation if it was preceded by the presentation of a congruent symbolic gesture.
2. To describe the temporal characterization of the motor activation and if it corresponded to a specific covert semantic understanding of the word.
3. To verify if the explicit constrain between an word and a motor schema is crucial to involve motor systems in semantic processing of abstract language.
4. To investigate if the literal description of the gestures posture activated more powerfully the motor cortex, since it literally described a movement.
5. To clarify if gesture and words can be understood within the same modal system.

Experiment 5 aimed at determining whether a motor simulation was performed after word presentation preceded by a prime gesture. With respect to experiment 3 and 4 the TMS was applied in correspondence to the target presentation. In fact, in this experiment we were not interested in measuring motor activation in response to a primary elaboration of the stimuli, but we wanted to measure how the previous processing of a symbolic gesture at motor level (at 100 ms delay) could influence a subsequent lexico-semantic analysis of a congruent word or pseudoword.

We used as stimuli emblems and words that could be congruent on the basis of meaning, or on the base of the literal description of the movement expressed by the word. The task was task similar to studies 1 and 2. The prime duration was always 100 ms, because that time corresponds to the motor simulation of gesture (see results of study 2) but we applied TMS to hand M1 100, 250 and 500 ms after target onset.

If stimulation is effective 100 ms post-stimulus we hypothesize that motor simulation is used to understand and compare gesture and word meaning. Furthermore, we were interested in comparing the activation of symbolic words with respect to the activation of literal words.

We hypothesized that MEPs would increase in the case of presentation of either literal or symbolic words with respect to pseudowords in the early time of processing, as it happened for prime gesture in experiment 3.

Furthermore we expected a possible difference in the activation between literal and symbolic words, because of the strength of the semantic relation between emblems and corresponding-in-meaning words, or because of the implicit motor command described in the literal word.

6.3 Materials and Methods

Participants

One sample of fourteen participants (12 females, mean age of 22.3 ± 1.3 years) took part in one TMS experiment. The participants were right-handed (according to Edinburgh Handedness Inventory, Oldfield, 1971) and Italian native speakers. They had normal or corrected-to-normal vision and no history of neurological or psychiatric disorder; furthermore they declared to have no contraindication to the application of single-pulse TMS (Wasserman et al., 1998; Rossi et al., 2009). The Ethics Committee of the Medical Faculty at the University of Parma approved the study. The experiment was conducted according to the principles expressed by the Declaration of Helsinki. All the participants in the present study provided written informed consent.

Stimuli

The stimuli were primes and targets presented in succession. The primes were the following: three pictures showing actor's postures corresponding to different symbolic gestures (Fig. 10). The targets were six pictures showing the still actor with a strip on which one of three symbolic words congruent with the meaning of the gesture, or one of three words expressing the literal description of the gesture posture was printed (Fig. 10, Table 2). In other six pictures, the actor presented pseudowords that were anagrams of words in which one or two letters of the presented corresponding symbolic or literal words could be changed. Nevertheless, the pseudowords could be easily read. A further picture of a black cross printed on a grey background was presented as target as a control baseline stimuli. In each picture the actor was facing the video-camera, and showed the gesture with the right hand without producing any facial expression. No audio was associated to picture presentation. Table 2 reports the presented meaningful gestures, and the corresponding symbolic or literal words and pseudowords. The words were clearly not matched in terms of length and occurrence because literal words were constituted by an expression of two words (e.g., "pollice su", see table 2) and it was not possible to compare symbolic and literal words. However, the six pseudowords were matched in length with the three symbolic and the three literal words, respectively.

Gesture	Symbolic word	Literal word	Pseudoword (corresponding in length with symbolic words)	Pseudoword (corresponding in length with literal words)
Thumb up	Well (BENE)	Thumb up (POLLICE SU)	NEBA	LOPLICE US
Thumb down	Badly (MALE)	Thumb down (POLLICE GIU)	LEMA	LOPLICE UGI
Stop	Stop (FERMO)	Palm forward (PALMO AVANTI)	MERFO	MAPLO VANATI

Table 2:
Gestures and words (translated in English) presented in the experiment 5. In brackets the words in Italian.

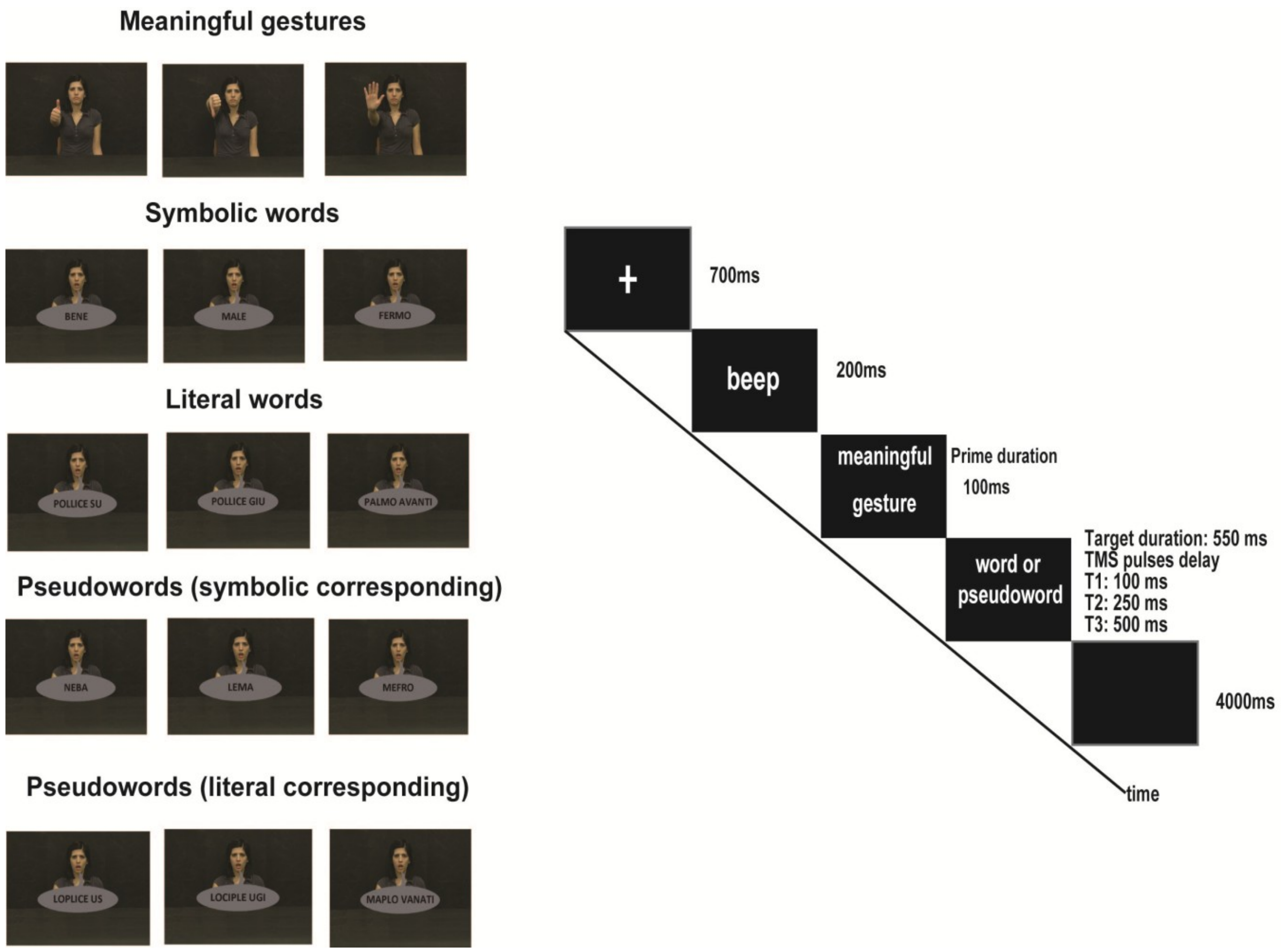


Figure 10. *Stimuli presented in experiments 5 and procedure. The left part shows pictures of meaningful gestures (upper part) and symbolic or literal (targets) words (lower part). The lowest rows show the pseudo-words used in the experiments matched with corresponding symbolic or literal words. The right part shows the procedure used in experiment 5.*

Procedure

The TMS experiment took place in a soundproofed room where participants seated on a comfortable armchair, with their elbow flexed at 90° and their hands prone in a relaxed position. We used a chin rest to keep the subject's head still. Stimuli were presented on a PC display (19 inches) placed on a table at a distance of 60 cm from the participant. The experimental procedure was programmed using Matlab software (MATLAB version 7.7, R2008b; Psychophysics Toolbox extensions, Brainard, 1997; Pelli, 1997; Kleiner, 2007) to control stimuli presentation and to deliver TMS pulses. The procedure was the following: pictures of an actor, randomly showing one of three meaningful symbolic gestures were presented after a fixation cross (700 ms, Fig.10). The duration of prime presentation was 100 ms followed by 50 ms of black screen (interval between prime and target). After turning off of each gesture, a picture with the still actor with a strip showing a word (symbolic or literal and congruent with the meaning of the gesture or a pseudoword was presented). Presentation lasted 550 ms (Fig. 10). In each trial, a single TMS pulse was delivered at 100, 250 and 500 ms after target onset (TMS delay). Each meaningful gesture was presented 2 times for each target and for each TMS delay (in total 108 stimuli). Baseline trials were run randomly during the experiment presenting the cross picture as target instead of a word/pseudoword for each TMS delay (in total 27 trials).

The task of the participants was to make a lexical decision classifying the target as a word or pseudoword. Specifically, in 30% of the trials, a question mark appeared after presentation of words/pseudowords and lasted 2000 ms. Subjects were instructed to pay attention to the prime and then to words/pseudowords. Participants decided whether the word/pseudoword had sense or not. They pressed a button with their left hand by mean of a button box in response to the word and pseudoword, respectively. Trials with incorrect responses and no responses were discarded for successive analysis.

Transcranial magnetic stimulation (TMS), electromyography recording (motor evoked potentials, MEPs) and data analysis (experiment 5)

A single-pulse TMS was delivered to M1. MEPs induced by TMS were recorded from the right first dorsal interosseus (FDI). Continuous EMG recording from FDI was acquired with a CED Micro 1401 (Cambridge Electronic Design, Cambridge, U.K.) connected to CED 1902 amplifier and interfaced with CED Spike software. EMG signals were amplified (1000×), band-pass filtered (20–2000 Hz) and digitized at a sampling rate of 5 kHz. Pairs of surface electrodes (Ag–AgCl, disposable, 7 mm × 4 mm) were attached, one to the belly of the right FDI muscle (active electrode) and one to the skin overlying the second metacarpophalangeal joint (reference electrode). The ground electrode was placed on the left wrist. Visualization and later processing of the EMG signal was done using Spike2 software (CED Ltd.). A figure-of-8 coil (Magstim Co. Ltd.) connected to a Bistim system (Magstim Co. Ltd.) was placed over the left M1. The intersection of the coil was placed tangentially to the scalp with the handle pointing backward and laterally at a 45°angle away from the midline. By using a slightly suprathreshold stimulus intensity, the coil was moved to determine the optimal position from which maximal amplitude MEPs were elicited in the controlateral FDI muscle. The optimal position was then marked on the scalp to ensure correct coil placement throughout the experiment. The intensity of magnetic pulses was set at 120% of the resting motor threshold (rMT), defined as the minimal intensity of the stimulator output that produces MEPs with amplitude of at least 50 μV in the muscle with 50% probability (Rossi et al., 2009). The absence of voluntary contraction was continuously verified visually throughout the experiment. When muscle tension was detected, participants were invited to relax and in the off-line MEP analysis, trials with muscle contractions not related to TMS were discarded.

MEPs of FDI muscle were visually inspected and rejected if they were contaminated by contraction not due to stimulation (0.7 % out of the total trials). The peak-to-peak amplitude (mV) of each MEP was computed by using MATLAB software (MATLAB version 7.7, R2008b). MEP amplitudes less than 50 μV were not considered (1.2 % out of the total trials). Normalized MEPs were calculated as variation of each value with respect to the mean of the baseline values. Mean values were submitted to repeated-measures ANOVAs with **target** (word vs. pseudoword), **type of word** (symbolic vs. literal) and **stimulation delay** (T1, 100 ms vs. T2, 250 ms vs. T3, 500 ms) as within-subjects factors. All post-hoc comparisons were carried out using Newman–Keuls test. Significance was established in all analyses at $p = 0.05$. No outliers were excluded because no MEPs amplitudes deviated more than 3 standard deviations from the mean for each condition within each subject. One participant was excluded for analysis because his mean MEPs values were significantly higher more than 3 standard deviation respect to the other participants. Sphericity of the data was verified prior to performing statistical analysis (Mauchly's test, $p > 0.05$). All variables were normally distributed as verified performing Kolmogorov-Smirnov Test (p N 0.05). η2partial was also calculated.

6.4 Results

The participants were able to recognize whether the presented stimuli were either words or pseudowords. Indeed, the mean percentage of correct responses was 96.9%.

Analysis of not normalized data

Raw mean MEP amplitudes of FDI muscle of baseline trials (cross pictures) administered during the experimental session with different TMS delays were not significantly different from each other ($F(2, 24) = 0.31$, $p = 0.73$).

Analysis of normalized data

To test the effects of linguistic stimuli presentation as compared with neutral stimuli, raw data for each participant were normalized, transforming mean FDI MEPs of both meaningful and meaningless symbolic and literal words into percentages with respect to mean MEPs of corresponding baseline stimuli. A repeated measures ANOVA was performed on normalized MEPs values, using meaning (words vs. pseudowords), type of word (symbolic vs. literal) and stimulation delay (T1 vs. T2 vs. T3) as within subjects factors.

The results of ANOVA showed a significant interaction between factor meaning and type of word ($F(2, 24) = 11.9$, $p = 0.005$, η^2partial=0.48), and between meaning and stimulation delay ($F(2, 24) = 3.9$, $p = 0.034$, η^2partial=0.25). MEPs increased in correspondence to presentation of symbolic words respect to literal words and pseudo-words (post-hoc: p=0.005, p=0.03, p=0,02; symbolic words=9.8% vs. literal words=1.9% vs. symbolic pseudo-words= -1 % vs. literal pseudowords = 3.5%). Furthermore, MEPs of words (both symbolic and literal) were significantly greater in T1 respect to T2 and T3 (post-hoc: p=0.04; p=0.05, T1=12.5% vs. T2=10.4% vs. T3=-5.5 %).

In addition there was a significant interaction between all the three factors ($F(2, 24) = 3.96$, $p = 0.033$, η^2partial=0.26, Fig. 11). The post-hoc analysis showed in particular a difference between the MEPs related to symbolic word condition at T1 and all the other conditions (post-hoc: symbolic pseudoword T1 p = 0.02; symbolic pseudoword T2 p = 0.5; symbolic pseudoword T3 p = 0.05; literal pseudoword T1 p = 0.04; literal pseudoword T3 p = 0.05; symbolic word T3 p = 0.002, literal word T3 p = 0.05) except for the condition literal pseudoword and symbolic word in T2 (post hoc: p=0.14, p=0.78). A trend to significance is also present comparing symbolic word to literal word both at time T2 (p = 0.07).

This result may depend on the fact that in case of prior gesture presentation, which implicated a motor simulation (see experiment 3), word processing caused an increment of MEPs of the FDI muscle, plausibly because the process of simulation of the posture related to the corresponding gesture was maintained to understand the subsequent word. Indeed, increment in MEPs was significantly greater for symbolic and meaningful words compared to pseudowords, so it is plausible to suppose that the meaning of the word (congruent with the gesture) was responsible of the effect.

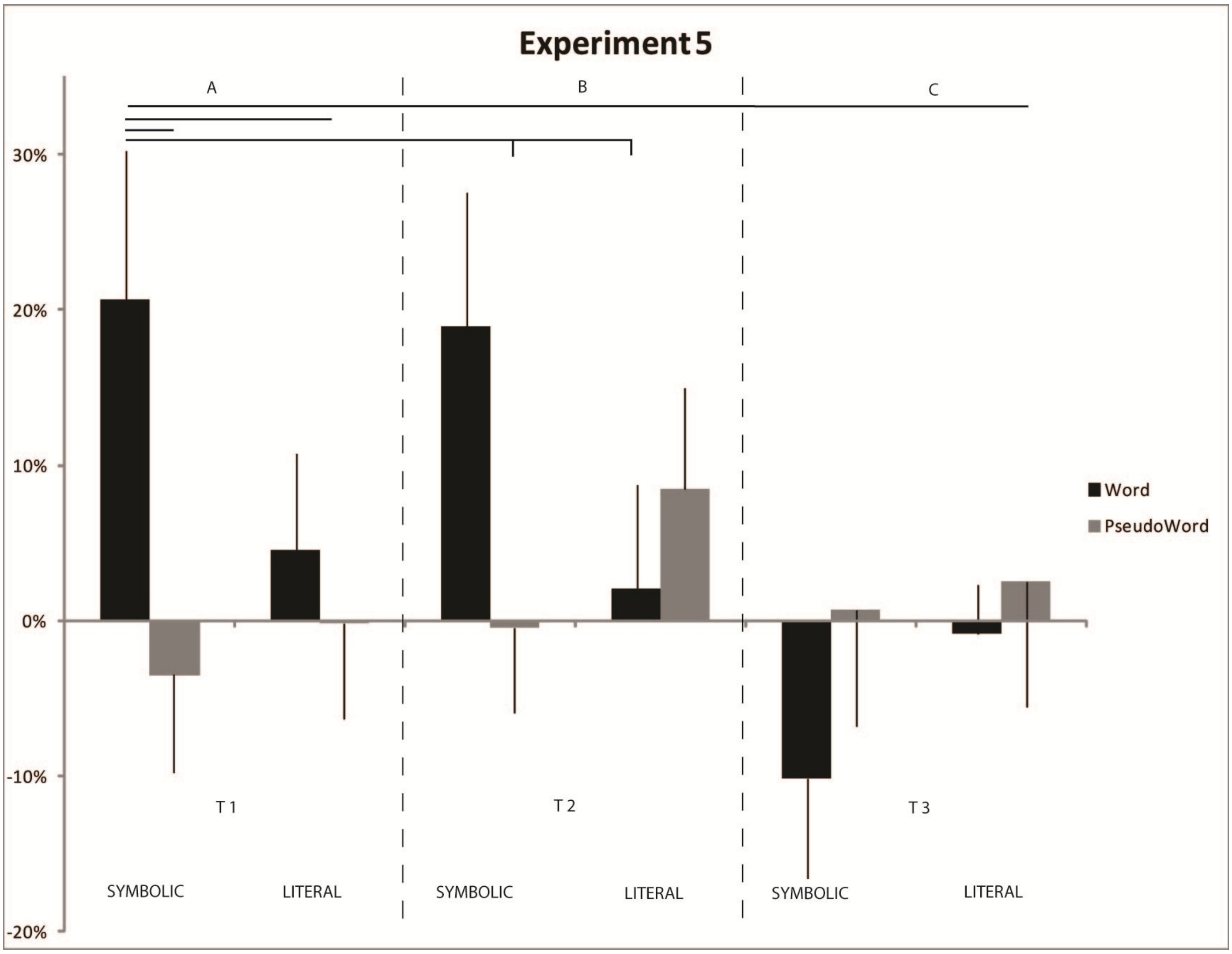


Figure 11. *Motor Evoked Potentials (MEPs) of FDI muscle recorded after single pulse TMS of primary motor area during presentation of target word; they are normalized with respect to baseline condition (cross presentation). Panel A, B and C represented T1, T2 and T3 stimulation delays (100 ms, 250 ms, 500 ms respectively). Black colours represented words, grey colours pseudo-words. Symbolic or literal labels described the type of word or corresponding-in-length pseudowords. Vertical and horizontal bars represent SE and significance in the statistical comparisons, respectively.*

6.5 Preliminary discussion

In accordance with the results of experiment 3 (Study 2) we can assume that in experiment 5 the prime picture of the actor showing a meaningful gesture automatically activated a simulation of the movement in order to reproduce that gesture. This activation was maintained in case of a subsequent presentation of a correspondent-in meaning symbolic word, within 100 ms after the onset of the target. We could hypothesize that gesture presentation, as in behavioural experiments (see study 1) facilitated the lexical access of a congruent word. We cannot speculate about the facilitation/interference effect in this experiment since we have not measured the response times of lexical decisions made about the target. However, the TMS effect was present only for meaningful words; this suggested that the activation found in M1 was strictly related to a lexical-semantic process.

Interestingly, symbolic word if preceded by a congruent gesture activated motor cortex within 100 ms after its onset that is the same time of motor simulation during gesture presentation, and decreased after during subsequent timing. This result confirm the involvement of motor cortex in semantic comprehension in the earliest phases of processing (Kiefer & Pulvermuller, 2012), giving strength to the idea that motor simulation can't be a corollary activation in semantic understanding. The absence of significant motor activation in the successive phases of comprehension is congruent with studies that found post-lexical processing in amodal associative areas that integrates concepts with different modalities (see Fabbri Destro et al., 2014). This opened the possibility of a subsequent involvement of multimodal areas after an initial comprehension though embodied simulation.

Despite they were congruent with gestures in terms of motor description, literal words did not activated M1 and did not differ from pseudowords. A possibility is that during speech the frequency of the association of the gesture with a corresponding symbolic word is significantly greater than the same association with a literal description. Difference in terms of frequency and length could affect semantic priming effect (Balota and Chumbley, 1984). Another explanation could be that frequency of gesture-word association affected the motor activation. If this frequency, expressed in terms of the probability of the co-occurrence of words with other words (or in this case, gesture with words) in the same sentence, or in general, in the same context (Landauer, 1998), measured a better learned association between a word and a specific motor posture, it is possible that more co-occurred words were stronger simulated. However, since it was not possible to compare the co-occurrence of gestures and symbolic and literal words, successive behavioural results should confirm this hypothesis, for example, showing a facilitated lexical decision (in terms of response times) in correspondence to symbolic than literal targets.

A final possibility is that the literal description of the gesture resulted redundant for the purpose of semantic comprehension. In fact, motor description does not add information about the meaning of the gesture, which resulted from participants' linguistic and cultural experience of the association of a specific movement to a specific meaning. Symbolic words instead, could give strength and confirm the communicative message. Although the literal words could evoke a motor activation related to motor content of the word, it is possible that this activation did not emerge or resulted weaker after a previous presentation of the same motor content in a visual/gestural modality.

Chapter 7 – General discussion and future research

7.1 Comparisons between the effects of prime gesture and prime word on target word

In study 1, the principal aims were to verify the existence of the integration process also when gestures and words were presented in succession and if the same mechanism that was evidenced for gesture and words characterizes communicative signals in general.

In experiment 1 the prime was a symbolic gesture. When it was meaningful and congruent with the target word it induced an increase in F1 only when the prime duration was 250 ms. In experiment 2 the prime was a word. When it was meaningful and congruent with the target word it induced an increase in F1, independently of prime duration. In experiment 2, the comparison with the baseline condition, showed a decrease (interference) when the prime and target were incongruent. Summing up, although the mechanism was equal, the integration was different when prime and target were both words since this was present for every prime duration, whereas in the case of prime gesture and target word it was present only in a specific period of prime presentation (250 ms) since it was successive to automatic motor simulation (100 ms, experiment 3).

Two processes can account for the interaction between gesture and speech; the first is the "facilitated lexical access", which postulates a facilitation in the lexical-semantic access when the gesture (or word) prime is congruent with the target word, whereas the second, the "integration" hypothesis, postulates that elaboration lengthens consequently to difficulty increasing in integration between two incongruent signals. Vainiger et al. (2014) proposed that "facilitated access" view is typical of lexical decision, whereas the "integration" process is typical of semantic judgment, which implicates a deeper semantic analysis of stimuli and higher loading cognitive processes. The present data can support the view of "facilitated access" in lexical processes since TRs decreased when the prime gesture was meaningful and congruent. However, in experiment 2 an interference effect could even be present if we take into account F1 production. This is in favour of the idea that lexical decision can be also associated to semantic judgment (Gulan and Valerjev, 2010).

In experiment 1 integration (variation in F1) was present at T2 (250 ms), whereas in experiment 2 it occurred at T1, T2 and T3. In experiment 1 motor cortex was activated during T1 probably to comprehend gesture meaning by means of motor simulation (see study 2, experiment 3). Successively, at T2, the motor-articulatory program of the word related to prime gesture meaning was activated and it modified the program of pronunciation of the target word. This effect was transitory because at T3 it was absent. In experiment 2 the prime word was automatically read and stored. When the target word was read, the prime word was retrieved and integrated with the target. Since hand M1 was not activated 100, 250, and 500 ms post prime word presentation, it is likely to suppose that motor simulation was not used for communicative word comprehension. A possibility is that a phonological representation of the prime was used. It was memorized and retrieved for comprehension and integration when analyzing target word. Summing up, comprehension preceded or was simultaneous to integration and the two process can be dissociated. Despite integration effect resulted similar for both communicative signals, in the case of symbolic gestures and words, it resulted from an interaction in the linguistic domain; Thus, if the initial representation of the two signals is not equal (i.e., motor or phonological domain), temporal features of the integration process could change.

6.2 Gesture and speech: one or two systems?

There are two points of view concerning the relations between gesture and speech. The first posits that gesture and speech belong to two different communication systems (Krauss and Hadar, 1999). Gesture functions as an auxiliary support when verbal expression is temporally disrupted or word retrieval is difficult. The second posits that gesture and speech belong to the same communication system (Gentilucci et al., 2006; Gentilucci and Corballis, 2006; Goldin-Meadow, 1999; McNeill, 1992) because they are linked to the same thought processes even if the expression modality differs.

In support of the first point of view is the following result of study 2. Gesture and corresponding in meaning word use different systems for initial comprehension. Gesture uses the motor system whereas word does not. There are studies

(Andric et al., 2013; Bookheimer, 2002; Chaminade et al., 2010; Ferri et al., 2014; Grezes, 1998; Lindenberg et al., 2012; Schippers et al., 2010; Villarreal et al., 2008) which show that the motor system is involved in gesture comprehension. In contrast, words related to symbolic gestures do not seem to access the motor system (Fabbri-Destro et al., 2014; Campione et al., 2014). In fact, abstract word comprehension (Scorolli et al., 2011; Sakreida et al., 2013) seems to rely more on linguistic systems whereas action word comprehension seems to rely more on sensorimotor systems (Buccino et al., 2005; Dalla Volta et al., 2014; Innocenti et al., 2013; Kiefer and Pulvermüller, 2012). However, in support of the second point of view are the results of study 1 and study 3. The same type of integration was present independently of the type of prime (i.e. gesture or word). Indeed, F1 of target word increased when prime gesture in experiment 1 and prime word in experiment 2 were meaningful and congruent with target word. Integration was explicated by an increase in frequency (lowering the tongue, Leoni and Maturi, 2002), that is in a more opened vowel. This posture (and consequently voice spectra), may communicate congruence with a previous prime signal and make unequivocal the meaning of the target word.

In study 3, results of study 2 (experiment 4) were partially integrated. When a communicative word is preceded by a congruent gesture, it was comprehended at the same motor level by means of motor simulation. In sum, gesture and words semantics is understood by the same modal system. This result is in line with the idea that abstract words did not activate sensorimotor areas because of their grade of variability with respect to a specific motor schema (Pulvermüller, 2013) and collocate them in a motor context could modulate the involvement of motor areas in semantic processing (Sakreida et al., 2013, Scorolli et al., 2011, Boulenger et al., 2009).

Thus, gesture and words, could be these cases understood by the same system, and motor activation seems to influence linguistic processing. However, results concerning the behavioural integration suggested a motor-to-phonologic transformation of the representation of gesture in order to interact with speech, at least for symbolic signals. At the present time, there is no according about the neural circuits probably involved in the integration mechanism. Gentilucci et al. (2006) found that the verbal response to gesture and/or speech induced an increase in vocal spectra when compared with the simple reading of the word. When stimulating left frontal area by means of r(repetitive) TMS (which induces interference), the gesture effects on the verbal response were transitorily suppressed. The stimulation of the right frontal area and sham stimulation were both ineffective. However, the spatial and temporal resolution of rTMS technique is low and consequently these results should be taken with caution.

Fabbri-Destro et al. (2014) by means of high density EEG recorded cortical evoked potentials of participants performing a semantic task during which a prime gesture was followed by a target word. They found larger negativity for N400 signal when gesture and word were incongruent in meaning. Source analysis showed activation of anterior temporal lobe (ATL) for the congruence and incongruence between the two signals and an initial activation of posterior temporal area for incongruence.

ATL activity can be involved in integration; indeed it is not modulated by the semantic relation between gesture and language but it plays a role in the interplay of these multimodal inputs. ATL can be included in the list of the possible “semantic hubs” (see Chapter 2) and its activation seems to be independent from modality of the stimuli (Bozeat et al., 2000; Coccia et al., 2004; Rogers et al., 2004; Warrington, 1975); this region might constitute a possible integration centre bringing together modality specific information in order to form an amodal semantic representation (see Visser et al., 2009 for a meta-analysis of 164 neuroimaging studies). However, activity related to N400 potential generally reflect post-lexical processes of language elaboration and could not clarify the previous role of sensorimotor areas in gesture and words comprehension. Indeed, motor activation in TMS studies 3 and 5 was found in the initial phase of stimulus processing (100 ms). A recent MEG study of Mollo and colleagues (Mollo et al., 2016) reported an influence of preliminary voluntary motor system activation in language processing, which was the modulation not only of sensorimotor areas but also linguistic areas (i.e. left temporal lobe), reflected in a modulation of ERPs, during a lexical task on action words.

In sum, we have to conduct more studies about gesture and words to design the exact spatiotemporal course and the brain circuits involved in their comprehension and integration, in order to describe the functional role and of motor system and other associative linguistic areas.

6.3 The challenge of abstract language: a parallelism with gestures

Results of study 3 brought new data about the question unsolved of the systems involved in abstract language understanding. Indeed, compared to other gestures like pantomimes, symbolic gestures may represent meanings that can be "translated" with a word categorized as more abstract than concrete. A proposal about the difference between concrete and abstract words, and, of consequence, about the neural circuit involved in their processing, regards the different way of learning of the two categories. While concrete language could be learned directly through sensorimotor experience, abstract language is probably learned more linguistically than perceptually (see Borghi and Binkofski, 2014). This parallel processing takes place most probably within different anatomically predefined routes. This theory coexists with proposals about the existence of a multilevel distributed representation of language, where sensorimotor traces exist in a variable measure and could depend from the referent express by the meaning conveyed from the word and from the variability of different contexts that can change that meaning (Pulvermüller, 2013). This could explain the different grades of activation between different words with concrete or abstract characterization.

As symbolic gestures could be the result of a secondary progressive conventional lexicalization of manual postures derived from previously learned motor schemas, abstract words could be a later conventionalization of meaning related to a wider range of more grounded concepts which abstract concepts were associated and learned through a more linguistic/social way. In this sense, as words could be categorized along a "continuum" from extreme concrete to extreme abstract meanings, also gestures could be classified from a manual posture strictly related to a specific action meaning (i.e. transitive actions and pantomimes), to a broader related one, more influenced by culture and social interactions. This parallelism could explain the difference about the level which gesture and words exactly interact. Studies of Gentilucci and colleagues (2001, 2004a, 2004b, 2009) suggested that the link between gesture and words exists at motor execution level between transitive actions and production of simple syllables. However, the presented studies evidenced that in case of symbolic signals, the interaction can occur at an higher linguistic level. It is possible that this relation could change in function of the “conventionalization” of the signals, that is the progressive distance between concrete language that expresses specific motor schema and more abstract concepts, which in terms of gesture production represents the continuum from transitive actions to symbolic language. Further studies will confirm this possibility, trying to define temporal and formal features of integration between gestures and words along the continuum (Kendon et al. 1982, 1988; McNeill et al., 1992), in order to evidence the eventual variability of the relation between gestures and words in function of the grounding level of the language.

With experiment 5 it was demonstrated that reducing the variability of the association of a symbolic word to a specific motor schema (i.e. introducing a motor context) could involve motor areas in processing abstract language.

A future possibility could be to propose a study where participants could be trained to associate a specific word to the execution of a semantically congruent gesture and to verify if motor cortex could be involved in comprehension of symbolic words presented without a gestural context because of residuals of learning, and how much this effect would last.

Glenberg, Sato, and Cattaneo (2008a) and Glenberg et al. (2008b) suggested a causal link between the motor system activation and the comprehension of both concrete and abstract language. In a behavioural study (Glenberg et al., 2008a), showed that use-induced neural plasticity in the motor system affected processes involved in the comprehension of both concrete and abstract language.

Vicario et al. (2013) trained participants to associate nouns of famous athletes (soccer or tennis players) to corresponding sport actions made with foot and hand. After some days of association training, MEP’s corresponding to foot or hand muscles were significantly modulated during a TMS experiment where participants were presented with the trained nouns. A similar mechanism could be tested with gestures and words, stressing the association between a word and a specific posture in order to reduce the variability of association of a word with a specific gesture at the minimum level.

In conclusion, gesture and words could interact at initial processing level (signal comprehension) as at final output level (signals production and control). This is in favour of a theory of **integration between the two communication systems,** although comprehension and integration between communication signals could involve different processes and brain areas. However, the role of motor system seems to be modulated by different factors that partially deal the problem of language grounding. Future research will have the goal to build a complete model that describes the interaction of communicative signals from the initial understanding phase to the final stage of production, and the brain circuits involved in this process.

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