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THE RELATIONSHIPS BETWEEN LANGUAGE AND ACTION: THE CONTRIBUTION OF VIRTUAL REALITY IN THE DOMAIN OF EMBODIED COGNITION

Coordinatore: Ch.mo Prof. Claudio Albino Bosio

Tesi di Dottorato di: Claudia Repetto

Matricola: 3810429

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To Sofia

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INTRODUCTION: GENERAL OVERVIEW

The present work aims to investigate the role of action and motor system in language processing. The link between language and action is not a totally new issue: in the 1950s Liberman proposed what is known as the "Motor Theory of Speech Perception", later developed and revised to accommodate new findings (Liberman & Mattingly, 1985), and recently reviewed by Galantucci et al. (Galantucci, Fowler, & Turvey, 2006). According to the original claim, speech is perceived by intending the movements of the vocal tract of the speaker: the focus of the attention is not put on the sounds pronounced but rather on the motor programs underlining them. But it's only on the last decades that the discovery of *mirror neurons* in monkeys, and of the correspondent *mirror neuron system* in humans, renewed the interest in this topic. Thanks to neuroscience facilities, nowadays a great corpus of experimental data has been collected that supports the hypothesis of a tight link between language and motor system.

In the present research this topic is addressed by using different methodics, and in particular the contribution of virtual reality to the study of language from an embodied point of view is tested.

The thesis is ideally divided in two main sections: the first one is a theoretical overview of the main theories of language, followed by an in-depth examination of the main issues addressed in the experiments, that is language processes and virtual reality; the second one is the experimental section, in which the three studies are reported. In the next paragraph a detailed description of the chapters will follow.

In the first chapter different theories of language and cognition will be described: traditional positions that consider language as a set of abstract operations managing symbols and amodal representations will be contrasted with the more recent concept of embodiment. This chapter represent both an historical excursus of the modern concept of language, and a comparison of different theoretical positions. The first theory taken into account will be the Universal Grammar by Noam Chomsky, who is the most influent supporter of the formal nature of language. Afterwards, the cognitive-functional approaches will be presented, whose proposal shifted the attention to a strong functional and cognitive commitment. Finally two different embodied approaches will be described: the Perceptual Symbol Hypothesis by Barsalou, and the Indexical Hypothesis by Glenberg.

For each different theoretical position a special focus on its claims about the acquisition and the evolution of language is provided.

The second chapter is dedicated to a literature review about the experimental data that support the embodied vision of cognition in general and of language in particular. The revision will be organised by distinguishing the studies according to the tool used to investigate the relationships between action and language: transcranial magnetic stimulation (TMS) and functional magnetic resonance (fMRI). The examination will underlie similarities and differences in findings with respect to the experimental procedure, the task or the tool used.

The third chapter aims at presenting Virtual Reality (VR) and its capabilities in neuroscience research. First of all, a general description of the elements comprised in a virtual reality system and their options of use will be illustrated. Furthermore, the concept of presence will be introduced: presence is a cognitive process with different facets, relevant not only during virtual experiences but also in the interaction with the real world. This neuropsychological phenomenon is coherent with the embodied view of mind and with the neurophysiological data arising from mirror neurons studies. The chapter will proceed taking into account the current use of VR in neuroscience research, and in particular the possible contribution of VR in the domain of embodied language research will be explained; finally, the third chapter will end up considering the potential use of VR in the rehabilitation of language deficits, and its rationale.

Chapters four to six will report the three experiments conducted to investigate the link between action and language. The first one aimed at investigating the role of the primary motor cortex during language comprehension, using rTMS; the second introduced the VR to understand if and how a virtual action modulates language comprehension; the last one, using the same virtual environments as in the second one, evaluated the role of the virtual action during second language learning.

Finally, the last chapter (number seven) will summarise the main results of the studies and will provide some concluding remarks about the state of the art of the findings, and the future researches that could be conducted to answer the open questions.

CHAPTER 1

LANGUAGE: DIFFERENT APPROACHES

The study of language all along fascinated scholars of different disciplines. For centuries, philosophers, linguists, psychologists focused their attention on few fundamental questions that has been matter of debate: what is the nature of language? How can a baby learn language? Where does language come from, from an evolutionary standpoint?
Different theoretical traditions proposed very different answers to these crucial questions, but it's with Chomsky and the Cognitive Revolution of the 1960s that a new era began. From then on, the coming of neuroscience and the availability of tools that allow seeing what happens in the brain during a given cognitive process (EEG, fMRI, MEG and so on), provided some new insights about the language, the brain, and the links between the two.

1.1 THE FORMAL APPROACHES

The formal approach to language is mostly instantiated in the work by Chomsky. One of the credits that should be given to Noam Chomsky is that he renewed the attention toward language as psychological phenomenon. In the previous decades, the father of the experimental psychology, Wilhelm Wundt, assigned to the language the status of human cultural artifact *(Völkerpsychologie)*, and as such it was supposed be studied in the natural sociocultural context. But the psychologists' general attitude in those years privileged the laboratory well controlled experiments, and for this reason the investigation of language has been mostly neglected. The Chomsky's work, by opposite, aimed to formulate classical problems in novel and suggestive ways that integrated language and mind. The main opinion on which the chomskian theory is grounded is that language is a psychological fact, and as such it deserves a scientific approach. This point of view was a kind of novelty for the period, neither it was shared in the scientific community: not only behaviourists didn't agree with this statement, but also other psychologists showed different positions about the necessity to investigate language. Wolfgang Köhler, for instance, was convinced that "mental facts" can not be actually find out, in the sense of the discoveries achieved by natural sciences: indeed, human beings don't have any intuition about physics concepts, such as the gravitational constant, but by opposite they have a sort of familiarity with all the mental events, which are, at least partially, obvious and intuitive.

On the other hand, Chomsky pointed out the necessity to investigate the factors involved in complex mental facts and to provide explanatory theories, without taking for granted their knowledge. The reason why we can't assume that language, belonging to the category of mental facts, is entirely transparent for humans is that it is regulated by a set of very abstract mechanisms and factors, which are not directly accessed. This set of rules is called Universal Grammar (Chomsky, 1965), and includes the principles necessary and sufficient that a system has to meet to be qualified as a potential human language. Thus, the normal abilities to understand and produce language, which are a quite automatic processes for humans, require the hearer/speaker not only to decode the structure of the sentence, as it has been expressed (surface structure), but also to access the core syntactic structure, that is not immediately available (deep structure). At the deep structure level the syntactic information is specified following the rules of the Universal Grammar; thus, the sentence by means of transformations is organised into different ways at the surface level, becoming the utterance actually pronounced/heard. The transformations, indeed, are formal operations of very abstract nature which human are completely unaware of.

So, the system of representations, rules and operations involved in natural language have in common the high level of abstraction and the complete remoteness from other mental processes. The idea of an "organ of language", dissociated from other cognitive abilities has been later taken up by one of the Chomsky's student, the philosopher of mind Jerry Fodor. In his book "The modularity of mind" (Fodor, 1983), Fodor proposed that the cognitive architecture is designed in *modules,* which are vertical structures deputed to the analysis of a certain kind of input. Language and visual perception are typical cognitive modules, and as such have nine distinctive features:

- domain specificity: they are highly specialised in order to process a particular type of stimulus;

- mandatory operation: when the specific input to which they are sensible is present, their activation is automatically triggered by the input;
- limited central accessibility: the intermediate levels of processing are relatively inaccessible to the consciousness
- fast processing;
- informational encapsulation: during their work, they cannot access other kind of information belonging to other modules;
- shallow outputs: the outputs are computationally cheap and usually refer to the basic level of a concept (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976)
- fixed neural architecture: the modules inhabit localised neural regions;
- characteristic and specific breakdown patterns: the dysfunction of a specific module affects the behaviour in a specific and predictable manner (i.e. aphasia and agnosia);
- Characteristic ontogenetic pace and sequencing: the acquisition passes trough precise steps along the individual's growth and maturation.

In summary, the basic argument of formal approaches relies on the distinction between *nature* of language and *use* of language: the former is mostly specified at the syntactic level, and its investigation led to the claim that all natural languages have in common abstract grammatical rules (Universal Grammar); the latter takes into consideration aspects of general cognitive functioning (attention, motivation, intentions, among others) and environmental constraints (context of use, communicative purposes and so on), which do not tap into the "core" system of language. As a consequence, formal approaches limit their field of interest to the Nature of language, leaving the Use of language in the periphery.

<u>Evolution of language</u>: given the abstract nature of language, than it follows that supporters of the formal approach to language are strongly convinced of the human specificity of this ability. In Chomsky's opinion, the mental organisation necessary to produce and understand human language is something very different from and unrelated to other cognitive abilities. In this sense, it is impossible that other animals share with human beings this special mental organisation: from a biological point of view, language could not be evolved as a higher degree of intelligence, but rather is a "true emergence".

Acquisition of language: the problem of first language acquisition has been addressed by many psychologists and philosophers. Nelson Goodman (Goodman, 1967), for instance, claimed that first language learning is made possible by the previous acquisition of a rudimental "symbolic system" during the interaction with the environment. So, the child in the first years of life acquires a general framework upon which the language is built up later on. Chomsky directly criticise this point of view, arguing that there are no reasons to believe that the distinctive features of language (i.e. the distinction between surface and deep structure, the properties of transformations) are included somehow in this prelinguistic symbolic system (Chomsky, 2006). He proposes rather that the predisposition to learn the first language is innate, and is activated when the appropriate stimulation is provided within the environment (Pinker, 2007).

1.1.1 The formal approaches under neuroscience's lens: evidences and challenges

The advent and diffusion of neuroscience techniques in the last decades provided the Chomsky's prediction about the nature of language with a unique opportunity to undergo empirical verification. Whereas the study of language corpora allowed researchers to investigate the phenomenon "language" from an external point of view, i.e. starting from the final products (its actual realisations in different natural languages), the neuroscience methodics offered the advantage to have a direct look into the processes underlining language mechanisms while they occur, and their brain localisation.

The clear and strong predictions put forward by the formal approaches were ideally suited to be challenged according to the laws of experimental procedures.

One of the issues that grounded the Chomsky's proposal was the claim that language per se is a distinct cognitive module (Fodor, 1983). Furthermore, within language faculty, three levels of representation exist that build the architecture of every sentence: the phonological level (which pertains to the representations of the sounds), the syntactic level (which specifies how words are combined), and the semantic level (where the meaning of the whole sentence is assigned starting from the meaning of each single words). Even if the sense of the sentence is given globally by the converging information driven from the three levels that work in concert, it is possible to selectively produce violations in one level, keeping the others formally correct. Look at the following examples:

a. the teacher read a book

b. the teackre read a book

c. teacher the a read book

d. the dog read a book

In (a) the three above mentioned levels are all well constructed and yield a comprehensible English sentence, whereas in (b), (c), (d) systematically one level is violated, being the others spared (respectively phonology, syntax and semantics are violated). According to Chomsky's theory, syntax, phonology and semantics are submodules of the language faculty, and, as such, are independent from each other (Chomsky, 2002). This claim has been partially confirmed by studies that showed that semantic information is independently represented in the brain (Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Martin, Wiggs, Ungerleider, & Haxby, 1996; Perani et al., 1999; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996). Further evidence derives from researches aiming at isolating the syntactic level from the other ones in order to test the hypothesis that syntax is processed in specific cerebral regions (Moro et al., 2001). The innovation of this research resides in its methodological approach to the study of the syntactic module, so far being mostly entangled in semantic information. As it can be easily understood from the examples above, semantics and syntax cannot be unravelled in natural language sentences, since one violation at the syntactic level inherently yields an anomaly at the semantic one (see sentence (c)). Moro and collaborators, instead, found out a way that allowed them to disentangle the two levels, simply by using pseudo-sentences (i.e. sentences with the typical syntactic and morphological structure, but made up of pseudo-words) in place of meaningful sentences. Critically authors constructed different types of sentences, one perfectly well-formed according to phonological and morfosyntactic Italian rules, and the others violating one of the levels at a time. Participants were requested to detect the anomalies while undergoing a fMRI scan.

Brain activations during the task evidenced a specific pattern of activity in case of morphological and syntactic violations which included the Broca's area, the caudate nucleus and the cerebellum, which has been taken as a proof of the autonomy of syntax from the other language components.

In the same vein, the independence of thoughts from language processes is one of the milestone in Chomsky's approach (Fodor, 2008). The relations between language and thoughts have been a hot topic for centuries (Montague, 1970a; van Benthem & Ter Meulen, 1996). Is it possible to think without bringing language into play? Monti et al. (Monti, Parsons, & Osherson, 2009) addressed directly this question by contrasting logical inferences relying on sentential connectives (e.g., not, or, if . . . then) to linguistic inferences based on syntactic transformation of sentences involving ditransitive verbs (e.g., give, say, take). The formers are thought to involve only cognitive processes based on logic (not linguistic) reasoning, the latter clearly entail linguistic processes. Neuroimaging data showed distinct cortical networks for the two types of inferences: logic inferences activated regions that are claimed to be responsible for deductive reasoning (left rostrolateral -BA 10p- and medial superior -BA 8- prefrontal cortices) and that are localized outside the typical language circuits.

According to the authors, these findings make unsustainable the hypothesis that thoughts rely only on language and that language is necessary for accomplishing deduction.

Another main issue in the Universal Grammar theory is related to the rules that a natural grammar can implement. According to the "principles and parameters account", not all the conceivable rules are represented in the real languages. The basic criteria that a grammar has to meet in order to be instantiated in a human language are called "principles". One of them is the kind of relationship that links together the sentence's constituents and that are specified at the syntactic level. In fact, in every natural language, syntactic dependencies are established following the hierarchical phrase structure, and not a fixed linear order of the words (Chomsky, 2002).

In other words, there are no languages in which, for example, the subject's role is always assigned to the third word from the beginning of the sentence. On the contrary, the dependencies between the words are specified on the basis of the relative positions, and for these reasons are never "space-locked". The feature of recursion, that is the possibility to include one structure into another one in a virtually limitless fashion, allows the distance between the words to be infinitely expanded. In this perspective, the hierarchical rules are referred to as "Non Rigid Syntactic Dependencies- NRSD", whereas the linear, fixed-ordered rules are called "Rigid Syntactic Dependencies – RSD" (Tettamanti et al., 2009)

The following example, provided by Tettamanti and al. (Tettamanti et al., 2009), clearly illustrates the difference between the hierarchical and linear rules.

1	2	3	4	5	6	7	8	9	10	11	12
(a) if	John	comes	by	Saturday	then	Paul	will	leave	by	sunday	
(b) if	John	comes	to	my	house	then	Paul	will	leave	by	sunday
(c) if	John	comes	to	my	then	house	Paul	will	leave	by	sunday

The transformation between (a) and (b) is an example of how the recursion can separate words structurally linked together ("if" and "then") without affecting the correctness of the syntactic structure nor the meaning of the whole sentence: this is one instance of the NRSD.

Looking at the transformation between (a) and (c), the linear RSD rule can be found: according to such a rule, the distance between "if" and "then" is fixed (i.e. four words in the between), therefore when adding supplemental linguistic material the space-locked link is not affected, and the new words are positioned accordingly.

Accumulating experimental evidence seems to confirm the plausibility of the distinction between legal versus illegal syntactic rules, being only the former processed in the brain regions deputed to language (Musso et al., 2003; Tettamanti et al., 2002). In these studies researchers investigated the different cerebral activations triggered by a NRSD and by RSD. Typically participants were requested to learn new syntactic rules constructed either mirroring the Universal Grammar rules (i.e. hierarchical dependencies – NRSD), or violating them (linear dependencies – RSD). The striking results underlined that the brain is able to detect the UG violations, and as such treats them differently from natural language. In fact, learning legal rules selectively activated the Broca's area, which demonstrated its involvement in language learning. This effect has been replicated both with natural language learning (Musso et al., 2003), and in pseudo-sentence learning (Tettamanti et al., 2002).

However, it is worth noting that hierarchical rules are not only typical of human language, but also represented in other cognitive and non cognitive domains, including music (Patel, 2003), action control (Conway & Christiansen, 2001; Greenfield, 1991), visuospatial processing (Greenfield, 1991). This account challenged Chomsky's strong claim about the uniqueness of language among the cognitive abilities, but recently it has been accepted in the revised version of his Minimalist Program (Chomsky, 1995). The fact that NRSD rules, even exploited in other cognitive domains, share with those involved in grammar the same basic features is confirmed by the shared brain regions in which they take place [left Inferior Frontal gyrus IFG - (Tettamanti et al., 2009)]. According to the authors, the fact that non-humans primates are able to learn simple grammars based on linear relations, but they are unable to spontaneously acquire hierarchical rules (Fitch & Hauser, 2004; Friederici, 2004; Jackendoff, 1999; Kuhl, 2000; Terrace, Petitto, Sanders, & Bever, 1979), testifies the special role that these set of rules assumed in human cognition. On the other hand, though, the observation, in non-human species, of rudimental abilities to manage simple NRSD lead to the conclusion that, "*language emerged in the course of evolution by drawing on a set of cognitive and computational capabilities that, at least in a rudimentary form, are shared across higher vertebrates*" (Tettamanti et al., 2009). This view is still in contradiction with the postulate of discontinuity between the evolution of human language and all the other forms of communication.

However, in a recent positional paper (Hauser, Chomsky, & Fitch, 2002), proponents of the formal approach addressed the issue of evolution by admitting that, if non human beings are found to use recursion for non communicative purposes, then it is possible to figure out that, during evolution, the modular system of recursion became penetrable to the extent that humans could apply it to other domains, as in the case of language.

1.2 THE COGNITIVE-FUNCTIONAL APPROACHES

The Cognitive-Functional approach to language grew out of the work of several scholars starting from the 1970s. They are linguists and philosopher of mind interested in the relationships between language and mind, but not disposed to follow the footsteps traced by the prevailing linguistic trends, that is the Universal Grammar theory. According to Cognitive-Functional linguistics, the Chomsky's perspective on language is more appropriately described as a mathematical approach than as a psychological one. In fact, the strong claim of Universal Grammar is that there is a level of linguistic processing, the syntax, that is independent from all the others including semantics; this thesis has been postulated without any empirical testing, but rather is a formal description exactly as mathematics. The goal of Universal Grammar seems to be to provide an elegant description of the abstract rules that govern syntax, and the elegance *per se* is taken as a justification of the linguistic constitutive nature of these rules (Tomasello, 1998a). This lack of empirical verification has progressively moved away the chomskian formalism from the psychological plausibility of its tenets.

By opposite, the cognitive-functional approach aims to account for different facets that are deemed unavoidable in order to describe, understand and investigate the human linguistic ability. The following "commitments" summarise the topics proposed and, when necessary, the arguments in contrast with Chomsky's theory:

- the Cognitive Commitment: language is one of human beings' cognitive abilities, and as such linguistic structure should reflect general cognitive principles. In other words, there is nothing special in language, as the formal approach strongly claimed; accordingly, the modularity of mind is rejected;
- the Generalisation Commitment: not only the language itself is not a module, but also there are common structural principals shared by syntax, phonology, morphology, semantics and pragmatics, that are no longer considered distinct from each other, nor organised in significant different ways (Lakoff, 1991);
- The functional Commitment: one of the crucial milestones of this approach is the focus on the ultimate goal of language, which is supposed to be the communicative function. Language comes from the communicative needs of human beings, and this common scope is one of the universals that all languages share. This interest in the functional role of language leads to at least a couple of consequences (one procedural and one theoretical): on one hand it commits linguists and psychologists to adhere to an empirical paradigm of research, very concerned with the real instantiations of the linguistics structures, whereas the Universal grammar was more focused on hypothetical

linguistic structures formally described and analysed; on the other hand, according to Tomasello (Tomasello, 2005), "language structures emerge from language use", that is the organisation of linguistic structures is directly related to how the language is actually used by the speaker. The distinction between competence and execution in not accepted, since language use and language knowledge are integrated;

- The Embodiment Commitment: cognitive processes, including language, are embodied by nature. Unlike proponents of the formal approaches, which argue that language being a "stand-alone" mental faculty can be investigated in isolation (Montague, 1970b), cognitive linguists emphasized the role of the human experience, which is in turn moulded from human bodies and neurobiological constraints, in language organisation. A deeper discussion about the embodied theories of cognition is reported in the next paragraph.

Cognitive-Functional perspective, given the broad theoretical accounts addressed, which earned it the label of Enterprise, over the last decades had an influential impact in the scientific literature and produced a plenty of contributions in many linguistic domains: semantics (Fillmore, 1982; Talmy, 1985, 2000), grammar (Fillmore, 1988; Langacker, 1987), metaphor and metonymy (Lakoff, 1990), concepts representation (Fauconnier, 1997, 1998; Fauconnier & Turner, 2003; Turner, 1996; Turner & Fauconnier, 1995), connectionist models of language learning (Bates & MacWhinney, 1981), pragmatics (Geeraerts, 1995), language acquisition (Tomasello, 2006).

A thorough description of each single research vein is beyond the purposes of the present chapter, but few points deserve to be sketched, since they are in direct opposition with respect to formal approaches' statements.

One of this is the role of meaning: cognitive-functional linguists propose the centrality of meaning as opposed to the supremacy of syntax, claimed by Chomsky. According to this view, language referents are the "objects" that are in the speaker's mind, rather than those located in the real external world. This position is often referred to as "representational", since it posits the equivalence between the semantic structure and the conceptual structure. In other words, the meaning reflects the concept one has about a given object, not about the object per se (Evans, Bergen, & Zinken, 2007).

However, this view does not imply that concepts and semantic items are identical: as pointed out in a clear example by Langaker (Langacker, 1987), there are “pieces” of the world that are represented at the conceptual level (i.e. the area of the face above the mouth and below the nose, where the moustaches are placed), but that do not receive a label at the lexical level. However, the lack of a word to denote this body area does not prevent everybody from understanding what moustaches are (that is hairs that grow in that specific body area).

This representational perspective found support in the observation of the variability of meaning embedded in the same lexical item. Let’s consider the following example provided by Fauconnier and Turner (Fauconnier & Turner, 2003):

(a) the baby is safe

(b) the beach is safe

(c) the shovel is safe

The word “safe” assumes different nuances depending on the word which is referred to: in (a), safe = who is not supposed to be in danger; in (b) and (c) safe = which is not supposed to put in danger someone else. These examples illustrate how the meaning is constructed by means of selection, choosing the one that is more appropriate in the specific context of use.

The importance of the <u>use of language</u> (mostly neglected by proponents of formal approaches) leads us to talk about the second issue that differentiate the cognitive-functional perspective from the formal ones: the hypotheses about the syntactic competences in children. In one of his influential papers, Tomasello (Tomasello, 2000a) analysed the content of the children’s utterances and linguistic expressions, providing hypotheses about the processes underlining their development toward adult’s competence.

The basic statement from which his proposal starts is the denial of the continuity between child’s and adult’s syntactic competence: according to the author, both records of spontaneous child’s speech (Pine & Lieven, 1993; Tomasello, 1992) and systematic experimental researches (see (Tomasello, 2000a) for an extensive review) collected data that challenge the “continuity assumption”, claimed by Chomsky.

The core structure of the adult’s language is not a discrete entity, but rather a structured inventory of constructions, some of which are more often produced and similar to each other, so that they constitute the core-like constructions, and some others that are linked to few other constructions and, as such, reside in the periphery. The proposed structure is very similar to a connectionist model. One of the central elements is, for example:

(a) I eat an apple

whereas a more peripheral one is:

(b) Him being a doctor!

In fact, (a) is the typical SVO English structure, wile (b) is a quite weird English sentence, being the subject in the accusative form.

Researches in developmental psychology underlined that children's linguistic production is not very abstract, even if it can include abstract content sentences. On the contrary, the process of acquisition seems to start with the learning of item-based linguistic constructions (such as verb island) by means of imitation, passing trough analogy making and structure mapping, to end up with structure combining.

During the first step of acquisition the child approaches language by means of intentions reading and cultural learning. This process is different from the mere mimicking, in that the young child is able to understand the intentions underlining the behaviour he is imitating. To say it with Tomasello's words "*understanding a communicative intention means understanding precisely how another person intends to manipulate your attention*" (Tomasello, 1998b, 2001).

The second step is characterised by the emergence of other cognitive processes needed to get closer to the adult's abstract language and productivity: analogy making and structure mapping allow to recognise similarities between structures that are well-formed on both syntactic and functional levels (i.e. the verb islands **give-tell-show-send** have in common the structure NP+V+NP+NP[1], and furthermore share the meaning of "transferring something to someone").

The third step refers to the combinations of previously acquired structures to form more complex utterances. Figure 1 describes how a young child combines together two two-words clusters learned separately (structure 1: *see [something/someone]*; structure 2: *daddy's [something]*). The curious thing is that the final product of these

[1] NP: Noun Phrase; V= verb

combinations are not embedded constructions, but rather isolated items, as described in the lower section of Figure 1: the sentence *I think* is used as an independent item, to the extent that usually it does not undergo transformations (passivisation, conjugation, recursion and so on).

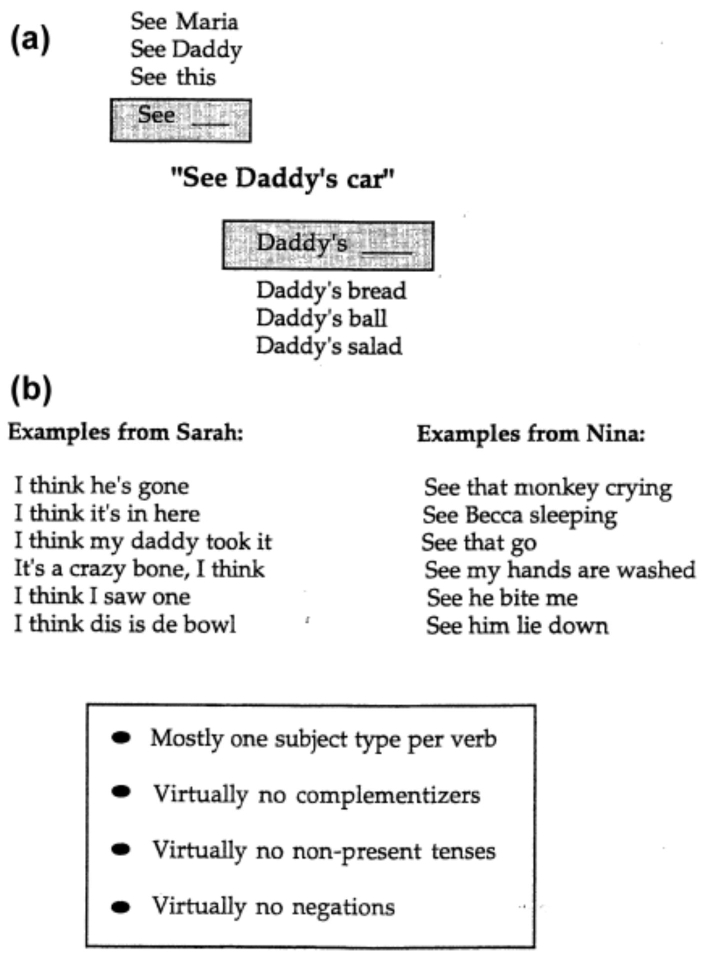

Figure 1: in (a) some examples of structures combining from the Tomasello's child; in (b) some examples of the earliest sentential component sentences reported by Diessel et al. (Diessel & Tomasello, 2001). (Figure reprinted from (Tomasello, 2000a))

In conclusion, this theory about language development stresses the importance of a **usage-based approach**, because, as pointed out by the author "*all linguistic knowledge – whatever abstract it may ultimately become – derives in the first instance from the comprehension and production of specific utterances on specific occasions of use*" [(Tomasello, 2000b) - page 238].

Evolution and acquisition of language: the central point where arguments about both evolution and acquisition converge is the *innateness* issue. This is an important matter of debate between cognitive-functional and formal linguists. The main idea of the formers is that language ability is NOT innate in the sense the lasts claim, but is still innate in a different meaning. In particular, Tomasello (Tomasello, 1995) argued that surely humans have a biologically predisposition for language, in that they are endowed with a set of cognitive and communicative abilities that allow a specific language to be implemented. The idea that is strongly rejected is that there is a special gene for language, or even for syntax: the fact that language ability is species-specific does not tell us about the nature of this feature (i.e there are several typical human behaviours, such as eating with the hands, but this does not mean that there are correspondent genes as well – i.e. an "eating-with-the-hands" gene, (Bates, 1984). The universals, differently from Chomsky's theory, are thought to result from human cognitive and social commitments shared by all the people: the language evolved in the way we know because human beings, independently from the concrete realisation of a specific language, had to solve the same problems and to meet the same needs in terms of communication and interaction.

Finally, as better stated in the previous section, the cognitive-functional approach proposes that the acquisition of language from childhood arises following the steps of the cognitive maturation. In particular, children acquire language from adults around them gradually, over a long period, by applying their general socio-communicative and cognitive skills (Tomasello, 2006).

1.3 THE EMBODIED APPROACHES

The embodied cognition approach gathers together neuroscientists, psychologists and linguists who reject the idea of a cognitive system designed to manipulate symbols and make abstract operations. By opposite, proponents of embodiment claim that the mind is inherently embodied, because the perceptual and motor system influence the way we construct concept, make inferences and use language. The Cartesian dualism between mind and brain is deemed incorrect, since mental operations are strictly related to, and dependent by our bodies. The embodied cognition approach, nevertheless, doesn't rely on a monolithic, unified theory, but rather entails different theoretical positions whit multiple facets that sometimes differ significantly from each other. From a methodological standpoint, all embodied theories share the commitment to a strong empirical and experimental grounding, and many researches take advantage of neuroimaging techniques and psychophysiological measures in order to make inferences about brain activity.

In the following paragraphs two theoretical proposals will be presented, the Perceptual Symbol System (PSS) by Barsalou and the Indexical Hypothesis (IH) by Glenberg: the first theory grounds language on perception, whereas the second points out the important role of action during language comprehension; the last introduces the next chapter, which is dedicated to a thorough description of a very productive line of research, concerning the relationship between language and motor system. This topic will be the "file rouge" of the experimental section.

1.3.1 Perceptual Symbol System (PSS)

The Perceptual Symbol System theory starts from the premise that cognitive processes are inherently perceptual, in that they share the systems with perception at both cognitive and neural level. In his position paper, Barsalou (L.W. Barsalou, 1999) reminded that the idea of a perceptual grounding of cognition is not totally new in the philosophical domain: rather, up to the 20th century the dominant idea was that knowledge is related to perception (some notable examples are Aristostele, Epicuro, and, getting trough the centuries until more recent years, Locke, Kant and Russel); afterwards, amodal theories of mind appeared in the scientific background and swept aside all the proposals that belong to the mentalism framework, including perception-based theories of knowledge.

A perceptual symbol is "is a record of the neural activation that arises during perception" (ibidem). It corresponds to an unconscious neural representation that is stored in long-term memory during a perception, serving as a symbol. Importantly, a perceptual symbol is not a "picture" of the entire brain state that underlies a perception, but instead it is a small subset of states selected by attentional processes. For example, when perceiving an apple, different kinds of neurons are activated to represent all the features of this object. The selective attention operates in order to select the subset of neurons that code for the apple's shape, and a record of this configuration of activated neurons is stored in memory linked to the apple's round shape. This operation is coherent with the Hebbian theory of synaptic plasticity (Pulvermuller, 1999).

The symbol formation process takes place not only following visual perception, but also during auditory, gustative, olfactory perception, proprioception and introspection. According to Barsalou's theory, it is likely that each type of symbol, arising from different sensory modalities, is stored in the correspondent sensory brain area. As a result, the theory predicts a brain damage in a specific sensory area should affect the correspondent sensory-specific knowledge (A. R. Damasio & Damasio, 1994; Gainotti, Silveri, Daniele, & Giustolisi, 1995; Pulvermuller, Lutzenberger, & Preissl, 1999; Warrington & Shallice, 1984).

The second main concept of the PSS theory is the simulation process. A simulation is a partial "re-enactment of perceptual, motor and introspective brain states acquired with the experience with the world, body and mind" (L. W. Barsalou, 2008). Actually, trough simulation, perceptual symbols are rehearsed from memory in order to represent the brain state associated with a given concept during past experience. Unless imagery, simulation is an automatic, unconscious process, and its pervasiveness trough different cognitive activities, suggests that simulation could be the core computation mechanism in the brain.

The PSS accounts for language abilities referring directly on the concepts of perceptual symbol, as the linguistic entity manipulated during language processes, and of simulation as the main computation process.

<u>Evolution of language</u>: the position of the PSS theory with respect the evolution of human language is in favour of the continuity with other species hypothesis. According to PSS proposer, the perceptual symbols systems are present in animals as well, and allow them to simulate entities and events belonging to their environment. The human linguistic competence, in this view, stems from an evolutionary upgrade of the pre-existing perceptual symbols system.

<u>Acquisition of language</u>: the ontogeny of language is deemed as closely linked to the perceptual symbols acquisition. First children acquire a consistent amount of

perceptual symbols grown out from the experience and develop the ability to simulate those symbols. By the time they are ready for language, this tremendous amount of knowledge already available supports language acquisition. As the skill progresses, humans become progressively able to construct simulations productively from others' sentences, or, in turn, to produce sentences capable to convey their own simulations.

1.3.2 The Indexical Hypothesis

Indexical Hypothesis (HI) has been proposed by Glenberg and Kashack (A. M. Glenberg & Kaschak, 2002). It is not to be intended as an explanation of language processes opposed to the PSS theory: the concept of perceptual symbol is fully accepted and integrated in this complementary proposal.

The main focus of HI is to account for the comprehension of sentences: according to this theory, the meaning of a sentence requires three steps:

1. indexing words and phrases to referents: the mapping may be done towards objects in the environment, or towards analogous mental representations of them, that are the related perceptual symbols (L.W. Barsalou, 1999)
2. extracting the affordances of the referents (Gibson, 1979), defined as the opportunities of action and interaction offered by a thing
3. meshing the affordances into coherent patterns of actions (A. M. Glenberg, 1997): this process is accomplished taking into account the intrinsic - biological and or physical - constraints (of the referent and of the human body), and the syntactic constraints.

The three steps are not sequential, but interact dynamically. To make clearer the processes let's have a look of the example cited by Kashack (Kaschak & Glenberg, 2000). Consider the sentence:

Lyn pushed the apple through the crevice using a crutch

Referents for Lyn, the apple, the crevice and the crutch are indexed and syntax (the identification of the subject, the direct object and so on) helps assigning to each element the correct position in relations to the other ones; the affordances for the apple, the crevice, and the crutch are extracted and the meshing process combines them into coherent patterns of action. As a result, the sentence may be understood, by assigning a plausible meaning. By opposite, the process of comprehension fails if the combination of the affordances results into an incoherent, undoable action (i.e. by substituting *the crutch* with *the thread*) (A.M. Glenberg & Robertson, 2000). Each time the affordances cannot be combined into a doable plan of actions, the comprehension of the sentence suffers, in that it is incomplete, or the sentence is judged nonsensical.

In other words, according to IH, language comprehension is accomplished by simulating the actions implied by the sentences. This statement is better explained referring to the Action-sentence Compatibility Effect (ACE), which predicts that the action described by a sentence may interact with a concomitant real action performed by the person: in short, the language content is able to influence the motor system.

In the classical experiment by Glenberg and Kaschak (A. M. Glenberg & Kaschak, 2002) participants were asked to make a sensibility task towards concrete and abstract sentences. All of them implied a transfer of something (real or symbolical) toward the reader (*Andy delivered the pizza to you* / *Liz told you the story*) or away from the reader (*You delivered the pizza to Andy/ You told Liz the story*).

The crucial element was the button box used to collect the answers: it was made up of three buttons, vertically oriented, and the starting position was always the middle button. In half of cases the “yes” button was the nearer, constraining the subject to perform a movement toward the body (consistent with a transfer toward the reader); in the other half conditions the “yes” button was the farer, inducing a movement away from the body (consistent with a transfer toward another person). Reactions times on corrected responses indicated that participants were faster when the movement required to make the response was consistent with that implied by the verb; the opposite was true for the reverse condition. Interestingly, these results were found for both concrete and abstract sentences. The authors explain this finding referring to the interaction between the simulation process and the actual movement.

<u>Evolution and acquisition of language</u>: this theoretical position is aligned with the previous one and for this reason is not further discussed.

CHAPTER 2

THE LINK BETWEEN LANGUAGE AND MOTOR SYSTEM

In the previous chapter an overview of the main approaches to language has been sketched. In the present one, I will narrow the frame of interest to deepen the perspective that inspired the following experiments: the theory based on the link between action and language.

The idea that language and motor system are not independent, nor free from reciprocal influences is not that recent: the Lieberman's Motor Theory of Speech Perception (Galantucci et al., 2006; Liberman & Mattingly, 1985) is one of the first theoretical proposals in this direction.

What is relatively new, and still growing, is the attention that neuroscience directed towards the hypothesis of a neural, besides cognitive, interplay between areas traditionally deemed to preside language processes and cortical regions belonging to the sensory-motor system. This vein of research is perfectly in line with the embodied theories of language, with which shares the basic assumptions.

Metaphorically speaking, embodied theories of cognition extended the boundaries of anatomical structures to which traditionally a specific function was assigned: the mind is no longer confined to the brain but also includes other body parts, such as hands, legs, eyes. Moreover, within the brain, the separation between primary areas, recruited for basic sensory and motor processing, and the associative areas, in which more complex processes take place is not strictly defined anymore: actually, the distinction between low and high level processes drops down in favour of a more integrated model. This new model proposes an interplay that allows the recruitment of primary areas even during cognitive processes such as language and conceptualisation. According to this account, the neural structures involved in sensory, perceptual or motor areas are also active when processing words whose meaning embeds prominent sensory [auditory and tactile features (Goldberg, Perfetti, & Schneider, 2006)], perceptual [color (Martin et al., 1995); faces and places (Aziz-Zadeh et al., 2008)] or motor features.

Even if the evidence of the contribution to language comprehension by perceptual and emotional systems (Havas, Glenberg, Gutowski, Lucarelli, & Davidson, 2010; Havas, Glenberg, & Rinck, 2007) is as strong as that by the motor system, the latter is more and more attracting the interest of the neuroscientists, also thanks to independent findings.

In fact, in parallel to these studies, the discovery of mirror neurons has brought new arguments for the anatomical and functional link between action and language. Mirror neurons, first found in the F5 area of the monkey brain, are a special population of cells that fires both during the execution of an action, and the observation of the same action performed by an other individual (Rizzolatti & Craighero, 2004). These neurons seem to be more sensitive to higher-level properties of an action, such as the goal, instead of the specific procedures carried out to reach the goal. Thus, neurons activated during the action of "grasping" fire regardless the effectors used (harm or leg) or the exact affordances planned (a peanut vs an apple). Since the F5 area in the monkey is thought to be the homologue of the BA 44 in humans, which is known as Broca's area, it seems consequential to consider mirror neurons as the biological foundation of the embodiment in action. In humans, being unavailable the single-neuron registration, we refer to mirror neuron system (MNS). Moreover, it has been found that a population of mirror neurons is specifically activated for actions executed with the mouth, and a small part of them, especially for communicative actions (Ferrari, Gallese, Rizzolatti, & Fogassi, 2003): this finding seems to provide the necessary bridge from "doing" to "communicating" (Chen & Yuan, 2008).

Starting from these considerations, the aim of the next sessions of this chapter is to briefly review the recent literature that addresses the relationship between motor system and language processing, distinguishing researches on the base of the tool used to investigate this issue (Trancranial Magnetic Stimulation – TMS or Functional Magnetic Resonance- fMRI). The intention is to show how and to what extent experimental protocols with different methodologies and tools lead sometimes to contrasting results; moreover a special attention will be paid to the discussion of the capabilities that each technique inherently presents.

<u>Evolution of language</u>: an interesting and fascinating hypothesis arising from this line of research is that language stems directly from action recognition. This theoretical

position, whose starting point is the discovery of the mirror neurons in monkeys and of the MNS in humans, proposes an evolutionary continuum, against the "emergence" hypothesis claimed by supporters of formal approaches. According to Arbib (Arbib, 2005), different stages divided the abilities known to exist in monkeys and apes from the modern language skills. On this account, the initial brain equipment necessary for the subsequent steps, entailed the mirror neurons, that allowed imitation. The process of imitation, in turn, evolved from a simple to more complex forms, supporting pantomime. The ability to perform pantomime is thought to underpin the development of a repertoire of manual gestures (protosign), which then supported the emergence of protospeech (a precursor of human language). In short, the language ability is achieved trough several evolutionary stages that made progressively the brain ready to language.

Acquisition of language: following the same premises, the acquisition of language is viewed as a process of maturation starting from the innate presence of the MNS. The MNS available at birth is rudimentary but flexible: later on it will be modulated by motor experience and visuomotor learning. This position is in line with that proposed by Tomasello (Tomasello, 2006), who underlined the importance of general cognitive abilities and their maturation in scaffolding language.

2.1 TMS STUDIES

Transcranial Magnetic Stimulation (TMS) proved to be an efficient and promising method to investigate the link between action and language. Thanks to its temporal and spatial resolution, TMS became one of the most used tools to study where and when the language processes are mapped within the motor system.

Most of the researchers applied single pulse TMS protocols over the primary motor cortex (M1) during a linguistic task and registered motor evoked potential (MEP) from the muscles that are supposed to respond depending on the portion of the cortex stimulated. The rational is the following: if the linguistic task engages to some extent the portion of the cortex stimulated at the time of stimulation, then it should result in a modulation of cortico-spinal excitability and thus of the MEP amplitude (compared to rest condition).

This kind of experimental design has been mostly employed to investigate the role of M1 during the processing of abstract vs action verbs, but results are sometimes contrasting. For example, Papeo et al. (Papeo, Vallesi, Isaja, & Rumiati, 2009) reported an increase of MEPs recorded while participants read action verbs compared with what happened while they read verbs describing abstract concepts; by opposite, Buccino et al. (Buccino et al., 2005) described a reverse situation during language comprehension: MEPs recorded from hand muscles was lower while participants heard hand-related action verbs compared to foot-related action verbs, indicating an effector specific inhibition. Although these findings might seem incoherent, several different experimental features can account for them; one of these is the timing of stimulation, which is an important issue to consider when studying excitability of such dynamic systems. In fact, we can argue that stimulation of an area occurring just while the process is taking place should produce an interference effect, and hence an inhibition of that area; by opposite, a stimulation delivered shortly before the onset of the process in this given area might act as a prime and produce a sort of facilitation effect (preactivation) for that area. Papeo et al. (Papeo et al., 2009) evaluated the effects of TMS over M1 at different windows of time from the linguistic stimulus onset: they reported an involvement of M1 in the linguistic process only when stimulation was delivered after 500 msec post-stimulus, that is in the post-conceptual stage but not in the previous ones. This result would lead us to think that lexical-semantic processing of action verbs does not automatically activate the M1, whose activation is modulated in a top-down manner.

The second element to take into account is the specific linguistic task performed by participants. In literature we can find different researches that employed different linguistic tasks to evaluate motor activation, each of whom entailed different linguistic processes. In some cases lexical decision was required (Pulvermuller, Hauk, Nikulin, & Ilmoniemi, 2005), while others used reading (Fadiga, Craighero, Buccino, & Rizzolatti, 2002), semantic judgments (Buccino et al., 2005), imagery (Fourkas, Avenanti, Urgesi, & Aglioti, 2006), transformation tasks (Oliveri et al., 2004). Tomasino et al. (Tomasino, Fink, Sparing, Dafotakis, & Weiss, 2008) compared systematically the effects of different timings of stimulation during different kind of tasks (silent reading, motor imagery and frequency judgments) and found that M1 plays a role only during motor imagery, so they concluded that the recruitment of motor networks during language understanding is not required, but it occurs only when explicit motor simulation is requested. However, the effect of TMS in modulating MEPs during semantic judgments of nouns (natural vs tools; graspable vs ungraspable) has been reported, even without any overt motor simulation (Gough et al., 2012). The identification vs distinction of the simulation/imagery processes is still open, even if imaging data seem to support the distinction hypothesis [(Willems, Toni, Hagoort, & Casasanto, 2010) see below].

Recently TMS protocols have been employed to discover the role of morpho-syntactic features on the activity of M1: Papeo and colleagues (Papeo, Corradi-Dell'Acqua, & Rumiati, 2011) compared MEPs recorded during reading tasks of action vs abstract verbs presented using the first or the third singular person (I vs he/she); they found an increase of MEPs amplitude selectively for the action verbs at the first person, deriving from these data that motor simulation is facilitated when the conceptual representation of the verb includes the self as agent. Furthermore, a sensitivity of the primary motor cortex to the polarity of sentences was highlighted: active action-related sentences suppressed cortico-spinal reactivity compared to passive action-related sentences, and either active or passive abstract sentences (Liuzza, Candidi, & Aglioti, 2011).

Finally, TMS can be used in offline procedures, delivering repeated trains of stimulation over a period of time lasting several minutes (rTMS, or TBS) in order to modify transiently the cortical excitability and investigate the role of the stimulated area in a given process. In this case experimenters are not interested in defining the exact timing of the cognitive process but rather aim to discover if the area is involved in that process. To this field of application can be ascribed the studies carried out by Gerfo et al. (Gerfo et al., 2008), and Willems et al. (Willems, Labruna, D'Esposito, Ivry, & Casasanto, 2011). In both researches motor networks (primary and/or premotor cortices) are found to be functionally relevant in action-related language understanding.

Future studies are needed to investigate with offline (facilitatory and inhibitory) stimulation the role of motor areas in different linguistic tasks in order to deepen the knowledge about their function (causal or epiphenomenal?) during language processing.

2.2 IMAGING STUDIES

The Functional Magnetic Resonance (fMRI) is so far the imaging technique preferred by researchers who intend to shed light on the relationship between motor areas and language processing. While TMS studies allow to establish a causal link between experimental manipulations (i.e. site of stimulation) and behavioural tasks (i.e. linguistic tasks), fMRi experiments are correlational protocols by nature, giving the possibility to identify, among all the brain areas, those engaged during a specific process and a precise window time; further, fMRI allows to track down networks of activations, reflecting the dynamic features of the process under investigation.

A first line of research aimed to determine if and where language processing recruits brain areas usually activated during motor tasks (considered in a broad sense, i.e. motor observation, preparation, execution). This topic often intercepts and includes theoretical issues that arise from studies focused on mirror neurons. In fact, it is well known that mirror neurons in monkeys are activated not only by the observation of a movement performed by others but also when the noise associated to the action is heard (Kohler et al., 2002). In humans, action-related auditory inputs are well implemented in language stimuli: this happens in particular when sentences describing actions are presented auditorily. Many studies have been carried out to explore the possibility that the understanding of action-related sentence relies on the same observation-execution system by means of mirror neurons [see (Aziz-Zadeh & Damasio, 2008) for a review]. Most of these researches, relying on different linguistics tasks, reported a somatotopic activation of premotor cortex, primary motor cortex and Broca's region (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Hauk, Johnsrude, & Pulvermuller, 2004; Tettamanti et al., 2005). Interestingly, this pattern of activation is confirmed even in children (age 4-6), as described by James et al. (James & Maouene, 2009), indicating that the embodied nature of language makes its appearance early in child development, when the language is not wholly acquired. Nevertheless, it is note worthy that there is not a strong consensus about a somatotopic organisation of action words meaning representations: Postle et al. (Postle, McMahon, Ashton, Meredith, & de Zubicaray, 2008), combining functional MRI with cytoarchitectonically defined probabilistic maps of left hemisphere primary and premotor cortices, failed to find a

direct correspondence between the activations triggered by effector-specific action words meaning and those found during the real movement of the same effectors.
As it has been noticed reviewing TMS studies, even in this case the kind of task and the features of the verbal material seem to yield different results. Raposo et al. (Raposo, Moss, Stamatakis, & Tyler, 2009) comparing cerebral activation during when proposing different semantic contexts (isolated action-verbs, literal sentences, idiomatic sentences) found that neural response was maximum in motor areas for isolated verbs and minimum for idiomatic sentences, with literal sentences in the middle; following authors discussion, these findings suggest that motor response during language processing is context-dependent rather than automatic and invariable. From a similar perspective, Van Dam and collaborators (van Dam, Rueschemeyer, & Bekkering, 2010) examined brain activity during the semantic judgment of verbs describing actions with different degrees of kinematic details: a region within the bilateral inferior parietal lobule proved to be sensitive to the specificity of motor programs associated to the action verbs, with the BOLD signal being greater for the finest-grained actions.
Finally, fMRI can contribute to refine the theory of embodied language and also to test hypotheses that, if confirmed, can add data in favour of this theoretical position. In one recent research Willems et al. (Willems, Toni, et al., 2010) investigated the construct of mental simulation, which is thought to be one of the core mechanism of embodiment, but it is still unclear whether it is the equivalent to explicit imagery. In particular, the authors found that implicit simulation of actions during language understanding is neurally dissociated from explicit motor imagery, thus confirming that the two processes are distinct in nature. Furthermore, according to simulation hypothesis, as stated by Willems et al. (Willems, Hagoort, & Casasanto, 2010) "if understanding action words involves mentally simulating one's own actions, then the neurocognitive representation of word meanings should differ for people with different kinds of bodies, who perform actions in systematically different ways" (i.e. right vs left handers): this prediction has been corroborated by fMRI data which showed a preferential activation of the right premotor cortex during lexical decision on action verbs for left handers, and the opposite pattern of activation for the right handers.
As showed in this short excursus, fMRI studies gave an important contribute to the study of the link between language processes and perceptive brain areas, thus adding

essential pixels to the big picture of embodied semantics theory; however, beside traditional neuroscience techniques, such as fMRI and TMS, other tools could demonstrate great capabilities in this field of application: the next chapter is dedicated to the description of one of them, Virtual Reality.

CHAPTER 3

VIRTUAL REALITY: A NEW FRONTIER FOR NEUROSCIENCE RESEARCH

After having framed the theoretical underpinnings, I would like to present one of the tools I selected to investigate the link between language and motor system: Virtual Reality (VR).

In recent years, VR has been widely used and in different fields of science: surgery, psychiatry, neuro-rehabilitation, psychology. Moreover, thanks to its capabilities, VR has been recognised as a powerful tool in both research and clinical practice.

This chapter aims at focusing on VR's application in neuroscience. First of all the basic concepts on which VR is grounded will be described; afterwards, its use in neuroscience contexts will be examined, with a particular spotlight on the rational that motivates its employment for studying language from an embodied perspective. Finally, an outlook on why VR could be considered for future applications in language rehabilitation will be proposed.

3.1 VIRTUAL REALITY: BASIC CONCEPTS

Generally speaking, if we want to provide a definition of a virtual reality system (VR) we have to refer to a combination of technological devices that allows users creating, exploring and interacting with 3D environments. Typically, people entering a virtual environment feels like being a part of this world and has the opportunity to interact with it almost like he would do in real world: just turning around his head, a user can explore visually the scene, and with other user-friendly controls one can move through the environment, approach objects, select them, meet other people presented as avatars or video-tape.

To implement a complete VR set the following items are required (Burdea & Coiffet, 2003):

- a software that builds and manage virtual objects in order to create a realistic model of the virtual world. It holds a database of the available items and is design to handle the different features of the stimulus that make it real-like when interacting with it (geometry, texture, intelligent behaviour, hardness, inertia and surface plasticity);

- the input tools (trackers, gloves or mice) that send to the computer the position and the movement of the user in real time;
- the graphic rendering system that changes the environment coherently with the information acquired;
- the output tools (visual, aural and haptic) that return to the user a feedback of the interaction.

The adherence of the virtual experience to the real world rests mostly on three features: sight, hearing and interaction. The visual input may be provided by means of three devices: a computer monitor, a head-mounted display (HMD), or a CAVE system. The computer monitor is the most simple and less expensive solution: thanks to its good image quality and definition is able to perform an excellent graphic rendering of the virtual environment. On the other hand, the user is bound to constantly look at the screen to enjoy the experience, and the external, real world is anyway present in his visual field. For this latter reason, the computer monitor is considered a non-immersive device. The HMD is a visualisation helmet that conveys the computer-generated images to both eyes giving the illusion of the third dimension in the surrounding space. Thus the environment gains in depth and, in turn, the realism increases. The experience with HMD is defined "immersive" in that the user is completely isolated from the real world. The disadvantage of this system is first of all the price: even if with the progress of technology promoted in the last decades the creation of more affordable models (recently they are designed like eyeglasses), without giving up the quality, to date the monitor is the preferred choice by researchers who move the first steps in the field of virtual reality. From the experimental point of view, another important issue should be considered: the use of HMD sometimes induces side effects in predisposed users, such as nausea and discomfort.

The last cited system is the CAVE. It is device based on a projection system that involves multiple surfaces where the virtual environment is presented: the walls, the roof and the floor of this special room are screens showing the images of the environment, allowing the user to feel completely enclosed by it. The main advantage is the participant's total immersion, along with the opportunity to share the experience with multiple users at the same time; the high cost of the implementation, though, limits the use of the CAVE to big research labs.

Acoustic systems as well help users to give a meaning to the virtual experience. Aural devices may be head-based, like headphones, or standing alone, like speakers. The formers are frequently used in association with HMD, and account for the need to prevent users from external distractions caused by natural sounds. The lasts, nevertheless, are often coupled with the CAVE or the monitor and allow the experience to be shared (Sherman & Craig, 2003).

Finally, the degree of interaction relies on multiple factors. Probably the most influent is related to the capabilities offered by the software: the more the user sees their actions affecting the virtual world, the more he will feel immersed and engaged.

3.2 THE SENSE OF PRESENCE

What is presence? To answer this question is not a trivial deal.

Historically, the term "presence" appeared first in the scientific community during 1992, when Sheridan and Furness titled a new journal about virtual reality systems "Presence, Teleoperators and Virtual Environments". The original meaning referred to "the sense of being there" (Sheridan, 1992), and clearly focused on the relationships between the user and the technological device: according to this view, the presence is the effect experienced while interacting with and exploring a virtual environment. Thenceforth, many definitions were applied to the concept of presence, each one emphasizing a particular facet, but all of them to be interpreted in relations to technology. Here you are some of the most cited definitions:

- " a perceptual illusion of non-mediation" (Lombard & Ditton, 1997);
- " a mental state in which the user feels physically present within the computer-mediated environment" (Draper, Kaber, & Usher, 1998);
- " *the subjective experience of being in one place or environment even when one is physically situated in another*" (Witmer & Singer, 1998).

However, as pointed out by Biocca (Biocca, 1999), even if research on virtual reality had the credit to bring to the fore the concept of presence, it is unlikely that the sense of presence suddenly appeared only along with the arrival of VR.

More likely, presence is a more general feeling whose activation prescinds from the kind of environment (virtual or real) the subject is exposed to: there are not intrinsic differences between stimuli arising from the medium or from the real world – the fact that one can feel present in either the former or the latter depends upon the environment and the individual features, and, as an effect of the interplay between the two, upon what become the prevalent perception in any one time. The figure 1 visually represents how this continuous perceptual-motor loop reflects the ongoing process of real-time action-based perception, which changes dynamically as we move through and interact with the world in real-time (IJsselsteijn & Riva, 2003).

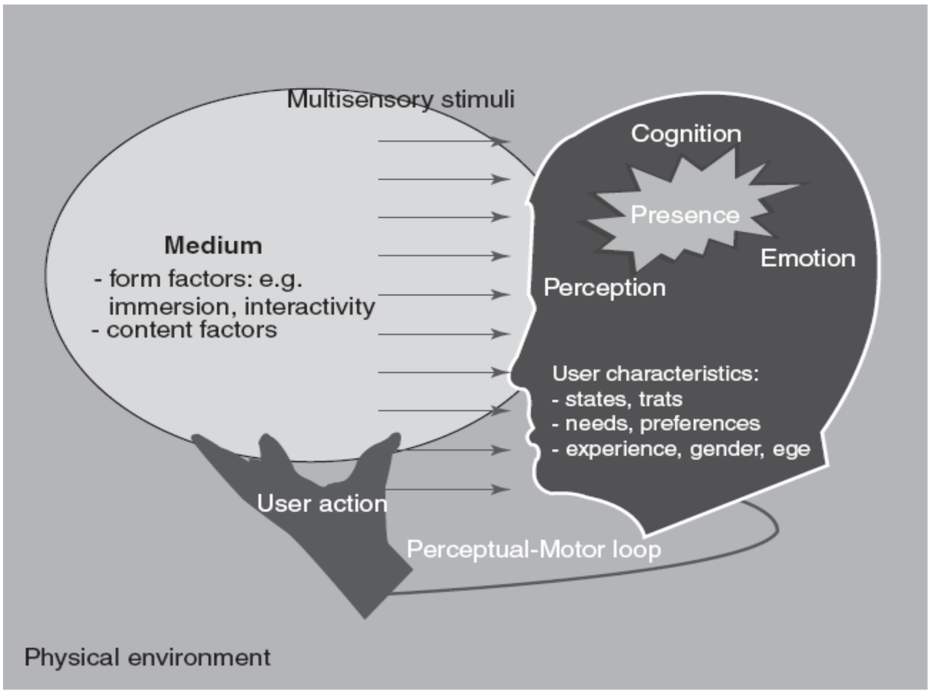

Figure 1: A general framework of presence [reprinted with permission from IJsselsteijn & Riva (IJsselsteijn & Riva, 2003)]

In the last decade, presence started to be considered increasingly a true psychological construct, with strong neuropsychological roots, evolved from the interplay of our biological and cultural inheritance (Retaux, 2003; G. Riva & Davide, 2001; G. Riva, Davide, & IJsselsteijn, 2003). The main goal of this phenomenon is supposed to be the control of agency. In fact, presence seems to be the missing bridge between the cognitive and volitional approaches to actions: the former focuses on the cognitive processes underlining the planning and the execution of an action, including motor programs needed to perform it; the latter focuses on the needs, goals, motives that motivate the subject to perform that action. In this perspective presence is "*the non mediated (prereflexive) perception of using the body/a medium to successfully transform intentions in action (enaction)*" (G. Riva, 2011). According to Riva et al. (G. Riva, Mantovani, & Gaggioli, 2004; Giuseppe Riva, Waterworth, Waterworth, & Mantovani, 2011), presence is a defining feature of the nervous system, necessary to differentiate between internal and external intentions. In other words this is the process that unconsciously monitors action and experience, yielding what is called the sense of agency, that is the feeling of being simultaneously the author and the owner of the action.

This process is achieved by virtue of a simulative forward model (Blakemore & Decety, 2001) which provides to the self a continuous feedback about the status of its activity: the sensory prediction of the outcome of the action [the simulation of the action consequences, according to the Covert Imitation Theory, (Knoblich, Thornton, Grosjean, & Shiffrar, 2005)] is produced together with the motor command. If the consequences of the action and the predictions match, presence increase and the self is able to concentrate on the action rather then on its monitoring. Figure 2 illustrates the simulative forward model.

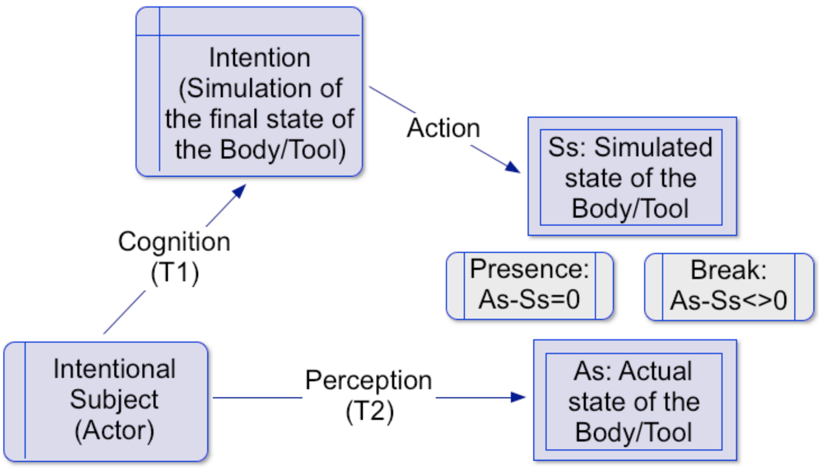

Figure 2: the simulative forward model [reprinted with permission from Riva and Mantovani (G. Riva & Mantovani, 2012)]

This approach to presence perfectly fits with embodied theories of human cognition (Shapiro, 2011).

Furthermore, the concept of presence as a neuropsychological phenomenon with the previous described features finds support in the recent mirror neurons' discovery (Rizzolatti & Craighero, 2004). These special cells fire when both we perform an action and we observe other conspecific performing the same action, and are thought to be the neural basis of several cognitive and emotional processes, such as imitation, learning, empathy. However, the mechanism of presence is needed to distinguish between the actual action of doing something and its mental representation.

Even if the presence is a unitary feeling, as a process it can be differentiated in different subcomponents (G. Riva, Waterworth, & Waterworth, 2004), coherent with the layers of the self proposed by Damasio (A. Damasio, 1999):

- proto-self: the pattern of neural activation that tracks the status of the physical status in real time;
- core-self: a transient entity that are generated when interacting with objects;
- extended-self: a systematic record of the invariants features the organism progressively discoveries about itself.

On the presence side, the three layers are the following:

- proto-presence: distinguishes the self from non-self, by coupling action and perception. In virtual worlds is often called "spatial presence" (G. Riva, Mantovani, et al., 2004) and is achieved by tracking the body position relative to the external world (appropriate updating of displays are required);
- core-presence: the ability to focus selective attention towards the sensorial experience, neglecting other stimuli. This is equivalent to "sensory presence" (e.g. in non-immersive VR) and requires good quality, preferably stereographic, graphics and other displays features.
- extended-presence: verifies the significance of the external world relative to the self. The more the experiences are significant, the more the self is present, and in turn it is able to reach goals in the external world. To be achieved, extended presence requires cognitive/emotional significant contents.

Figure 3 summarises the layers of the self and the correspondence with those of presence.

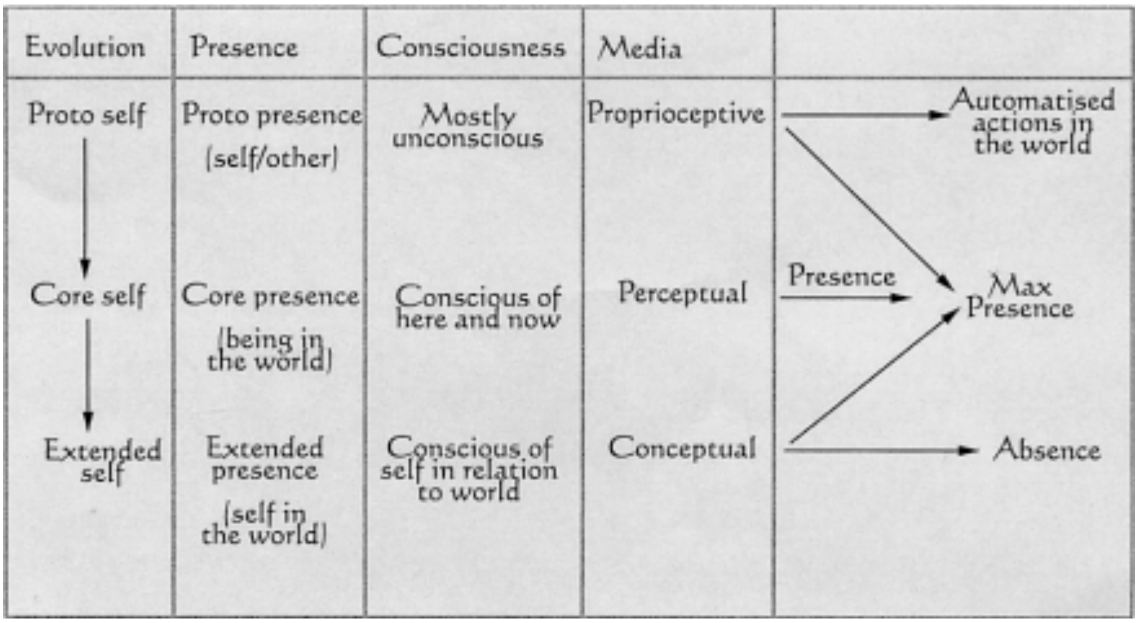

Figure 3: the layers of presence and the self [reprinted with permission from Riva and Watherworth (G. Riva, Waterworth, et al., 2004)]

3.3 VIRTUAL REALITY IN NEUROSCIENCE: WHY EMBODIED LANGUAGE COMES INTO IT

Far from being a merely recreational tool, VR is increasingly used in research and clinical settings (G. Riva, 2002). Traditionally, the most common application of VR in mental health is related to the treatment of anxiety disorders (Emmelkamp, 2005; Parsons & Rizzo, 2008): from simple phobias (Krijn et al., 2007; Barbara Olasov Rothbaum et al., 2006), to panic disorders (Botella et al., 2007; Vincelli et al., 2003) , post-traumatic stress disorder (Gerardi, Rothbaum, Ressler, Heekin, & Rizzo, 2008; B. O. Rothbaum, Hodges, Ready, Graap, & Alarcon, 2001) , and generalized anxiety disorder (Repetto et al., 2011; Repetto, Gorini, Algeri, et al., 2009; Repetto, Gorini, Vigna, et al., 2009; Repetto & Riva, 2011). The reason for the diffusion of the VR in this field of application is its versatility for implementing exposure therapy (VRET): in fact, VRET is safer, more controllable, less embarrassing and costly than in vivo exposure, but at the same time its immersive nature provides a real-like experience that may be more emotionally engaging than imaginal exposure (G. Riva, 2010).

Recently Bohil and colleagues (Bohil, Alicea, & Biocca, 2011) described the advantages of using virtual environments in several domains of neuroscience, such as spatial navigation, multisensory integration, social neuroscience, pain remediation, neurorehabilitation. Authors pointed out the capabilities of VR for implementing experiments that overcome traditional limitations encountered by researchers interested in understanding the functioning of central nervous system. One of these limitations is the gap between the degree of complexity typical of the real world and that embedded into the stimuli created ad hoc for the experimental protocol. In fact, usually participants in research settings perform tasks interacting with several different devices (i.e. computer, button boxes) none of which is designed to simulate the real experience where the process investigated occurs. Virtual reality, by opposite, allows to bypass the common criticism toward the experimental setting, that is its poor ecological validity: immersing participant in virtual environments one could gain ecological validity without giving up controllability and replicability.

For researchers interested in studying cognitive processes from an embodied point of view this is a great opportunity: if representations in the cognitive system are multimodal, then to investigate their properties one should recreate the multimodal experience that can trigger the process. Furthermore, with the advance of technology, the interface between subject and VR system is more and more intended to become a non-mediated process, in which the body itself is the navigation tool (without the need of control devices). For these reasons VR could be thought as an ideal medium for investigating several cognitive domains (G. Riva, 1998) but the capabilities are not confined to the fact that inside the virtual experience many different source of stimulation can work together to recreate a realistic environment. In fact, VR can be considered an "embodied technology" for its effects on body perceptions (G. Riva, 2002): it is possible the use of VR for inducing controlled changes to the experience of the body. On one side, VR has been used to improve the experience of the body in patients with eating disorders (Ferrer-GarcÍa & Gutiérrez-Maldonado, 2012; Perpiña et al., 1999; G. Riva, Bacchetta, Cesa, Conti, & Molinari, 2003) or obesity (G. Riva et al., 2006). On the other side, different authors used VR to induce illusory perceptions – e.g. a fake limb (Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2009) or body transfer illusion (Slater, Spanlang, Sanchez-Vives, & Blanke, 2010) - by altering the normal association between touch and its visual correlate. Being an embodied technology, VR seems a promising tool for the investigation of the link between language and action. In the recent past, the discovery of mirror neurons changed the outlook of neuroscience and established a connection between language and motor system (Chen & Yuan, 2008; Gallese & Lakoff, 2005).

The embodiment theory of language assigns an important role to this class of motor neurons in understanding action related concepts: mirror neurons should be activated by the linguistic stimulus and hence it should result in a modulation of the primary and premotor cortex (Gallese, 2008). As reviewed in the previous sections, several studies confirmed that language itself triggers motor-like responses within the cerebral areas where movement is represented (Buccino et al., 2005; Hauk et al., 2004). The opposite way to understand the relationships between language and action is to investigate if and to what extent motor inputs affect language representation and acquisition. Paulus and colleagues (Paulus, Lindemann, & Bekkering, 2009) asked participants to learn functional verbal knowledge of new objects while performing different motor tasks. They found the presence of motor interference when the acquisition of manual object knowledge was paired with the concurrent manual action but this wasn't true if concurrent actions with the feet were performed. Furthermore, Macedonia and colleagues (Macedonia, Muller, & Friederici, 2011) studied the impact of iconic gestures on foreign language words learning: if learning of novel words was coupled to iconic gestures participants retained better the verbal material over time, if compared with meaningless gestures; this behavioural data was accompanied to imaging data, that indicated an activation of premotor cortices only for words encoded with iconic gestures.

The researches that use actions for understanding the interplay between language, motor system and mirror neurons find in VR a privileged medium where being implemented. VR gives users the opportunity to see themselves moving in the environment while being comfortably seated in a chair. Thanks to different input devices participants could virtually perform any action, even those typically not performable in an experimental setting (to jump a rope, to kick a ball, to shoot something). Thus, within a virtual environment, experimenters could investigate the effect on language processing of performing different actions. The fact that users are not really moving their bodies in the real space, but still have the subjective sensation of being "in action", places VR in a intermediate position between the real action and mere action observation (such as in a video): it has been demonstrated that cortical excitability is modified by the observation of movements performed by others (Strafella & Paus, 2000), but this modulation is greater if the orientation of the movement is compatible with the point of view of the observer (Maeda, Kleiner-Fisman, & Pascual-Leone, 2002). The advantage of VR is the fact that the movement the individual does is egocentric, exactly as if he/she would act in real world.

As Cameirao has argued (Cameirao, Badia, Oller, & Verschure, 2010), the first person perspective could engage strongly the mirror neurons system because this is the perspective the system is most frequently exposed to. This observation has important rebounds in the field of rehabilitation: if the enactment of verbal material facilitates learning in non - pathological samples, it should be investigated if this effect is replicable in people with language deficit. Moreover, often patients with different type of aphasia have motor deficits as well, and VR could give them the opportunity to take advantage of the action-language coupling protocols even without moving at all.

Finally, VR experiments can be conducted also in association with imaging techniques, such as fMRI: further researches, thus, using virtual environments during fMRI scans could shed light on the cortical activations triggered by virtual movements, and on the role of mirror neurons in these processes.

3.4 VIRTUAL REALITY AND LANGUAGE REHABILITATION: DOES IT MAKE SENSE?

Traditionally, the rehabilitation of language disorders is administered trough speech therapy sessions, associated or not with technological devices (Fridriksson et al., 2009; Fridriksson et al., 2007; Laganaro, Di Pietro, & Schnider, 2006; Laska, Kahan, Hellblom, Murray, & von Arbin, 2008; Levin et al., 2007). Recently, however, new tools borrowed from neuroscience, demonstrated their capabilities in promoting the restoration of language abilities. In particular non- invasive brain stimulation (rTMS, tDCS) techniques proved to be efficient in enhancing language performance following brain damage due to both stroke or dementia (Cotelli, Calabria, et al., 2011; Cotelli, Fertonani, et al., 2011; Cotelli et al., 2012; Cotelli, Manenti, Cappa, Zanetti, & Miniussi, 2008).

The following section will try to discuss the potential use of VR, as another tool to be tested in contexts of language rehabilitation.

The use of virtual reality and new technologies for the assessment and the rehabilitation of deficits following brain damages has been widely investigated. The main applications of virtual reality in the field of cognitive rehabilitation are related to the following cognitive domains: memory, plan and motor abilities, executive functions, visuo-spatial representations (Morganti, 2004). In recent years a growing interest for this kind of applications led to the implementation of several virtual environments designed to the rehabilitation of cognitive abilities (Broeren, Bj√∂rkdahl, Pascher, & Rydmark, 2002; Broeren, Bjorkdahl, Pascher, & Rydmark, 2002; Davies et al., 2002; Kizony, Katz, Weingarden, & Weiss, 2002; Kizony, Katz, & Weiss, 2004). However, few researches investigated the capabilities of virtual reality for the ri-education of language. For example, Lanyi e coll. (Lanyi, Geiszt, & Magyar, 2006) created a software and a virtual home aimed to enhance naming abilities of common objects. Ahlsen (Ahlsèn & Geroimenko, 1998) instead, pursued different goals: the Virtual Communicator for Aphasics (VCA) is intended to represent a "Cognitive Prosthesis", in that it allows the patient to select one item and providing the correspondent vocal output (basically, the software names the object the patient is unable to name).

Furthermore, scientific proofs in the field of neuroscience support the hypothesis that virtual reality applied to the treatment of language deficits could have an added value with respect to traditional tools. One of the prominent features that makes virtual reality a promising tool to manage language deficits is its degree of Technology Engagement (TE): virtual environments, if conveniently designed, are able to promote both the sense of presence and the optimal experience of flow (Reid, 2004). Moreover, previous researches pointed out that virtual reality-based rehabilitation programs gathered high levels of interest and motivation compared to traditional programs in different samples of patients (Bryanton et al., 2006; Meldrum, Glennon, Herdman, Murray, & McConn-Walsh, 2012).

In particular, Pulvermuller (Pulvermuller & Berthier, 2008), by reviewing the recent findings in the domain of neuroscience, identified at least three main implications for the clinical practice related to language rehabilitation; we will list them below, underlining why virtual reality should address them better then other tools:

1. one of the main symptoms of aphasia is the deficit in action and objects naming, due to the weak connections between the representation of meaning and the correspondent word. These networks could be reinforced by means of coincidence and correlation learning. In operational terms, it means that rehabilitation protocols are more effective if the treatments are numerous and close in time, in order the foster functional activation of different neural systems.

   Advantages of virtual reality: the portability of such system (on smartphone, tablet) allows to repeat several times, at home and in the convenient moments, the exercises.

2. Language deficit can arise also from the mechanism of learned non-use. In fact, the patient tends to avoid the sentences and the word that is unable to name, because this attempt exposes him to frustration and anxiety. This habit causes a sort of vicious circle, in which the less a word is retrieved and pronounced the less it will be in the future.

   Advantages of virtual reality: the patient can train his residual abilities in a context that is both ecological and protected, and than he feels more comfortable and motivated to put himself on the test.

3. Recent neuroimaging findings established a tight link between language and motor system. In particular it has been shown that motor circuits are involved during language processing (Pulvermuller et al., 2005; Rizzolatti & Craighero, 2004): it means that that one could stimulate language through the action.

   Advantages of virtual reality: virtual reality is a privileged environment where the subject can act as if he was really moving, but being seated on a chair. He can therefore train a wide range of different action-words without moving at all. This is advantageous also for patient with motor deficits.

CHAPTER 4

EXPERIMENT 1: THE EFFECTS OF rTMS OVER THE PRIMARY MOTOR CORTEX DURING SEMANTIC COMPREHENSION

The present chapter will describe the study performed in order answer to following question: is the primary motor cortex (M1) necessary for language comprehension?
The present study, thus aimed at investigating the role of the primary motor cortex during verbs comprehension, within the framework of the embodied theories of language. I applied repetitive transcranial magnetic stimulation (rTMS) over the right and left hand portion of M1 and tested the effects of the stimulation toward the processing of hand-related action verbs versus abstract verbs. Results underlined a specific inhibition effect following left stimulation, only with hand-related action verbs. These findings seem to corroborate the hypothesis of a functional role of M1 in action verbs comprehension.

4.1 INTRODUCTION

According to embodied cognition hypothesis, cognitive processes rely on body states and experiences, and concepts are mapped within the sensory-motor system. In this framework, embodied theories predict that the neural structures involved in processing sensory information are also active when processing words whose meaning embeds prominent sensory features (Martin & Chao, 2001; Thompson-Schill, 2003); furthermore, it assumes that neural structures required to perform an action are also involved in processing words describing the same action. Both these predictions are supported by experimental data. On the one hand, it has been found that the generation of colour word triggers the activation of the ventral temporal cortex close to the colour perception areas (Martin et al., 1995); furthermore, Goldberg and collaborators (Goldberg et al., 2006) found that the retrieval of words with specific auditory, visual, tactile or gustative features activate the correspondent sensory areas in the brain.

Within this conceptual frame, one of the most intriguing topic, whose investigation generated a large corpus of data, is the link between language and motor system. Hence, many researchers are interested in understanding if, and to what extent, the motor brain areas are involved in action words comprehension. The role of the premotor cortices has been widely investigated with different methodics and different kind of language tasks (Hauk et al., 2004; Tettamanti et al., 2005; Willems et al., 2011).
The involvement of the primary motor cortex (M1) in language processes, instead, has been primarily studied using transcranial magnetic stimulation (TMS), which allows to establish a causal relationship between experimental manipulations (i.e. site of stimulation) and behavioural task. Applying single pulse TMS over M1, several researchers found a modulation of motor evoked potentials (MEP) recorded from the correspondent effector during different linguistic tasks (Fadiga et al., 2002; Fourkas et al., 2006; Oliveri et al., 2004; Pulvermuller et al., 2005), and at different timings (Papeo et al., 2009). For example Buccino et al. (Buccino et al., 2005) reported a decrease of MEPs amplitude registered from hand muscle while participants heard hand-related action verbs, compared to action verbs involving other body parts. The opposite findings are described by Papeo et al. (Papeo et al., 2009), who noticed an increase of M1 activity following semantic processing of action verbs compared with non-action verbs, but only when the stimulation was delivered 500 ms post stimulus presentation; the timing of the effect, according to authors, indicates that M1 is not automatically activated by lexical-semantic processing, but rather is involved in post-conceptual processing triggered by the retrieval of motor representations.
This issue opens a critical question about the role played by the sensorymotor areas in language processes: are they *necessary* for the comprehension of action-verbs, or is their recruitment epiphenomenal? Supporters of a strong embodied position agree with the first hypothesis (Gallese & Lakoff, 2005; Pulvermuller et al., 2005), whereas the alternative perspective points out that the activation of motor circuits could be interpreted as a “side effect” of the real semantic process (Mahon & Caramazza, 2008), and not a constituent part of the semantic process per se. The early cross-talk (within 200 msec) between language processes and overt motor behaviour, as reported by Boulenger et al. (Boulenger et al., 2006), suggests that the language-related activity in the motor regions is part of the language process and not a consequence of it.

Nevertheless, the co-occurrence between the modulation of cortical excitability and the linguistic tasks, evidenced using single-pulse stimulation, as suggested by Willems et al. (Willems & Casasanto, 2011), doesn't allow researchers to distinguish between the alternative hypotheses.

One way to disentangle this issue is through patient studies: the prediction of embodied theories is that lesions in sensorymotor regions should affect the processing of words associated to those sensorymotor features. However, to date this vein of research did not provide clear-cut evidences for two main reasons. On one hand, findings are somehow contrasting: Arevalo (Arevalo, Baldo, & Dronkers, 2012) failed to find a link between the site of the cortical region (primary and premotor cortex) and the correct responses to hand and mouth items compared with neutral control items; other studies, yet, highlighted a specific impairment of verbs processing in patients with different pathologies affecting motor functions, including vascular diseases (Berndt, Mitchum, Haendiges, & Sandson, 1997), progressive aphasia (Hillis et al., 2006)), motor neuron disease (Bak, 2010; Bak & Chandran, 2012), Parkinson's disease (Boulenger et al., 2008; Herrera, Rodriguez-Ferreiro, & Cuetos, 2012). Crucially, in these studies, despite their divergent data, authors mostly contrasted verbs versus nouns but never action-verbs versus non action-verbs, so that they can not rule out the possibility that findings were due to the fact that verbs in general are more difficult to process than nouns due to semantic, syntactic and morphological features (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Vigliocco et al., 2006).

An alternative way to address the "necessity question" (Fischer & Zwaan, 2008) is to exploit the capabilities of repetitive transcranial magnetic resonance (rTMS), which is able to induce a transient virtual lesion and to test the specific effect of the temporary deactivation of the stimulated area on a given task. This procedure recently has been applied by Gerfo et al. (Gerfo et al., 2008): authors asked participant to perform a morphological task following an offline session of low frequency (1 HZ) rTMS delivered on the left M1, and found a selective delay of the reaction times while processing action words, compared with state words.

The present study fits in with this line of research, and aims at shading further light on the role of the primary motor cortex during language comprehension.

We applied offline rTMS over the hand portion of right and left M1 in right-handers, and we evaluated the effects of the stimulation toward semantic comprehension of action verbs (compared with abstract words).

Our hypotheses are:

- if M1 is necessary for accessing semantic information of concrete action verbs, then the transient disruption of this area should affect the process, and should result in slower RTs compared to abstract verbs
- if action verbs comprehension processing is linked to the actual motion execution system, as predicted by embodied cognition theories, then the inhibitory effect of stimulation in right handers should be observed only after left stimulation.

4.2 MATERIAL AND METHOD

4.2.1 Participants

Twenty right-handed students, (6 males and 14 females; (age: range 19-36 years; mean: 24.45; st. dev.: 5.07; years of education: range 14-18; mean: 16.2; st. dev.:1,67), attending different classes at the Catholic University of Sacred Heart, have been recruited for the experiment, and rewarded for their participation with a breakfast coupon. Handedness was assessed using the inventory by Briggs and Nebes (Briggs & Nebes, 1975). Participants were all native Italian speakers, and had normal or corrected-to-normal vision. None of them was aware of the specific purposes of the study. Inclusions criteria followed the most recent guidelines for the use of TMS in experimental settings (Rossi, Hallett, Rossini, & Pascual-Leone, 2009). All the participants signed an informed consent in order to join the experiment. The experimental procedure, and the specific consent form describing it, had been previously approved by the University Ethic Committee.

4.2.2 Stimuli

Twenty-four concrete verbs and twenty-four abstract verbs were selected and matched for number of letters [$F(1,47)= 0.026$; $p= 0.873$], number of syllables [$F(1,47)= 0.648$;

p= 0.425], and frequency [F(1,47)= 0.033; p= 0.856] in order to form different blocks (see below for details concerning the blocks).

The concrete verbs described actions performed with the hand. They were selected from a larger corpus of 40 hand related verbs, which had been previously and independently evaluated by 30 students, comparable to the experimental sample for age and education level. In this pre-test phase, individuals were asked to indicate if the action depicted by the verb requires a body part to be performed, which one, and to rate the degree of imageability. The items included in the experiment have been unambiguously identified as hand-action verbs and with high imageability (see in the Appendix: Tables I and II for the list of items employed in the study).

After this pre-test phase, which allowed us to select the appropriate stimuli, three blocks had been constituted (each block was composed by 48 items). Items in each block were shown in a specific conjugated form[2], chosen among the first three singular persons of the simple past tense. This choice was made for two reasons: the first three singular persons were used in order the blocks to be differentiated; the simple past tense was used in order to be sure that presented verbs would be unambiguously considered as verbs, since a few of them could be intended as names if presented in a different form (i.e present tense).

4.2.3 Procedure

Participants were welcomed in a quiet room by an experienced researcher.

After reading and signing the consent form the experimental procedure started.

The main experimental task, that participants, as will be explained shortly, were asked to perform a few times, required participants to sit in front of a computer screen at a distance of approximately 50 cm. First of all, they read the experimental instructions, that were the following: " In the present experiment you will see one verb at a time in the centre of the screen; you have to press 0 if the verb is concrete, and 9 if it is

[2] Italian verbs have different morphological suffixes added to the verb root to indicate the different persons and the past tense. In our experiment we selected the simple past tense, wich requires to add the morpheme –av/-ev/-iv depending on the conjugation wich the verb belong to, plus the three singular persons (wich are respectively identified by –o/-i/-a). For example, the verb "firmare" (to sign) was presented in the three blocks in the following conjugated forms: firmavo; firmavi; firmava

abstract; please try to be as accurate and quick as possible". The keys 0 and 9 were replaced by 1 and 2 when the participants responded with their left hand. Then, in the centre of the screen, a fixation point was presented for 2 seconds; afterwards, an item (the first verb – verbs were presented in randomised order) appeared and the participants had to press the relevant key, according to the instructions received. The choice was made by pressing a specific key on the keyboard (one key was associated to concrete verbs, another, close to it on the keyboard, to the abstract ones). After the choice was made, or, in case of missing response, after 5 seconds, the item was replaced by the fixation point – and then by the subsequent item. The entire task lasted about 5 minutes. Reaction times were recorded using E-prime software.

The experiment itself was divided into two separated sessions, one for left and one for right stimulation, each consisting in two steps: the baseline condition (the task without stimulation), and the post-stimulation condition.

The order of the steps and of the sessions was counterbalanced across subjects, but always the experimental task was preceded by a training session, in which twenty items not included in the main task were presented in order to allow participants to familiarise with the task.

The first experimental sequence started with the baseline task, then the participant received the stimulation and, immediately after that, the post-stimulation task was performed. The second experimental sequence started with the stimulation, followed by the post-stimulation task, and finally, after at least one hour of delay (in order to allow the complete wash out of the rTMS effects), the baseline task was performed again. During each session, participants responded with the hand ipsilateral to the side of stimulation.

Repetitive Transcranial Magnetic Stimulation (rTMS) was delivered using a Magstim Super Rapid magnetic stimulator, connected with an eight-shaped coil (diameter of 70 mm). The site of stimulation was the hand portion of the primary motor cortex left and right. The localisation of the site was defined as the hot spot whose stimulation evoked the largest muscular twitch. The motor threshold was determined, according to Rossini et al. (Rossini et al., 1994), as the minimum intensity able to evoke a muscle twitch from the controlateral hand in five out of ten consecutive trials. rTMS was delivered in trains of 1 Hz and for a duration of 12 minutes; the intensity was set up at the 100% of the individual motor threshold intensity.

At the end of the experiment, participants were asked, for each concrete verb, to indicate if, and which, body part is required to perform the correspondent action, and to rate the imageability of the action.

4.3. DATA ANALYSES

As a first step, items to which an incorrect response has been given were excluded from analysis (0.02% of the total numbers of items). Then, we calculated the mean values for each subject and for each condition: the values that exceeded 3 standard deviations with respect to the correspondent mean value were excluded from analysis (0.01% of the total number of items). According to Data Quality Metrics rules, metrics should be directionally correct with an improvement in use of the data (Dasu & Johnson, 2003). So in our case, considering the role of individual differences (i.e. individual mean speed of response) unrelated to the experimental conditions, the raw RTs have been corrected in order to compensate for individual mean response time; for each condition, the following formula has been applied to each single RT:

$(RT_{after\ stimulation} – RT_{baseline})/RT_{baseline}$.

Corrected RTs, obtained from this calculation, expressed the effect of the stimulation in a given condition and were then analysed with repeated measures analysis of variance (ANOVA), with side (left vs right) and verb (abstract vs concrete) as within subjects factors. Multiple comparisons between conditions were calculated with Tukey's Test.

4.4 RESULTS

We found a significant main effect of the main factors [side: $F(1, 19)= 10.961$; $p= 0.004$; $\eta^2= 0.881$; verb: $F(1, 19)= 38.442$; $p< 0.001$; $\eta^2= 1$], indicating that, as a general trend, participants were faster when answering after the right stimulation compared to the left stimulation, and when answering to concrete verbs, if compared to abstract verbs. Moreover, a significant effect of the interaction site X verb [$F(1, 19)= 19.568$; $p< 0.001$; $\eta^2= 0.987$] was found (Figure 1). Post-hoc analyses demonstrated that RTs for concrete verbs after left stimulation were significantly slower than for concrete verbs after right stimulation (Tukey's Multiple Comparison Test; p< 0.05), as well than for abstract verb after left stimulation (Tukey's Multiple Comparison Test; p< 0.05): these results seem to underline a specific effect of left stimulation towards concrete verbs (see Table 1 for descriptives).

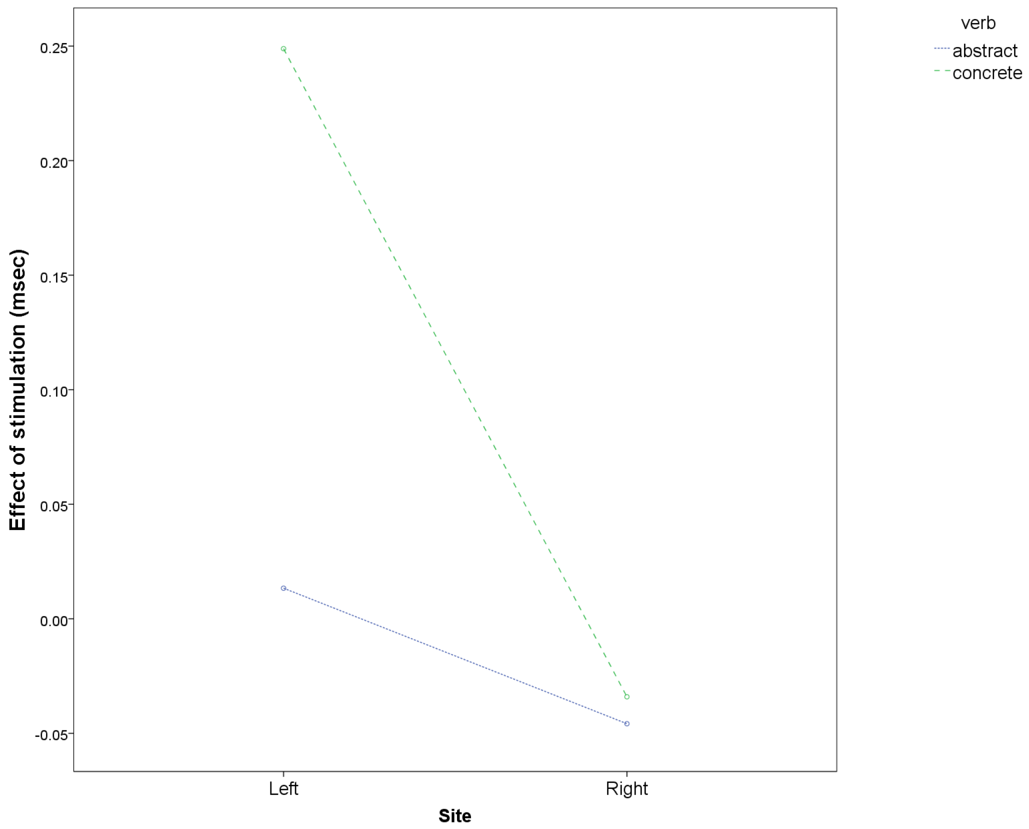

Figure 1: interaction between side (left vs right) and verb (concrete vs abstract). On the y axis, corrected RTs (in milliseconds) calculated with the formula (RTafter stimulation – RTbaseline)/RTbaseline are displayed.

Site	Verb	Mean	Std. Deviation
Left	Abstract	.013	.224
	Concrete	.249	.326
Right	Abstract	- .046	.170
	Concrete	- .034	.131

Table 1: descriptives of the effects of stimulation

4.5. DISCUSSION

The present study aimed to investigate the role of the primary motor cortex during semantic processing of action verbs. In particular, it was focused on addressing the *necessity question*, which wonders whether or not the recruitment of the motor areas is needed in order to understand words entailing motor content. To pursue these goals we applied rTMS over the hand portion of the right and left primary motor cortex and evaluated the effects of the stimulation toward a semantic comprehension task.

The main result of the experiment is that the stimulation affected selectively the processing of action verbs, but not that of abstract verbs: actually, RTs were slower after stimulation, compared to the baseline, only when verbs describing hand-action were presented; no differences in RTs were found between pre and post stimulation with verbs describing intellectual or symbolic activities. The present findings are in line with previous imaging and electrophysiological results (Hauk et al., 2004; Pulvermuller, 1999; Pulvermuller, Harle, & Hummel, 2000, 2001; Tettamanti et al., 2005): authors reported a somatotopic activation of the motor areas during linguistic processing of actions performed with different body parts, revealing a recruitment of the motor system elicited by non-motor tasks. Similar conclusions are drawn from several TMS studies, reporting an involvement of the primary motor cortex during language processing (Buccino et al., 2005; Fadiga et al., 2002; Gerfo et al., 2008; Meister et al., 2003; Pulvermuller et al., 2005; Sundara, Namasivayam, & Chen, 2001; Tokimura, Tokimura, Oliviero, Asakura, & Rothwell, 1996; Watkins, Strafella, & Paus, 2003; Willems et al., 2011). However, if the contribution of the motor areas is widely acknowledged, the direction of this involvement is still not clear. Our findings seem to indicate a facilitatory effect of the primary motor cortex on semantic processing, confirmed by the fact that the temporary disruption of that area resulted in a delay of the RTs with action verbs. These results agree with those of Gerfo (Gerfo et al., 2008), who applied offline rTMS over the primary motor cortex right before asking participant to perform a morphological task and described a slowing of the RTs for action words, but not for state words. Moreover, our results are compatible with studies that have found an increase of cortical excitability of the muscle effector, induced by a concomitant linguistic task. For example, Fadiga (Fadiga et al., 2002) showed that listening to phonemes increases the cortical excitability of the brain regions involved in their execution. Similarly, Pulvermuller (Pulvermuller et al., 2005) in an experiment that mirrors our own, reported a facilitation in response latencies to arm action words following arm site stimulation, and to leg action words after leg site stimulation. Authors stated that this differential effect of stimulation refers to a category-specific involvement of the primary cortex during lexical access.

On the other hand, Buccino (Buccino et al., 2005)reported the opposite effect: motor evoked potentials recorded from hand and foot muscles decreased while participants listened to hand and foot action-related sentences respectively. Authors explained these findings referring, among others hypotheses, to an interference effect exerted by a “higher order” motor representation of the heard action on all concrete motor representations needed to perform that action. From our perspective, there could be another possible explanation to integrate these apparently incongruent findings: the passive hearing of sentences, as employed by Buccino, does not imply a deep semantic processing of the material, as required by our task. These different levels of processing could contribute to elicit different responses of the primary cortex, depending on task demands: one could assume that motor areas are silent or slightly inhibited when the subject is not supposed to intentionally process the stimuli; however, as long as the task demands increase and the semantic level is approached, the contribution of the motor cortex become more active causing a facilitatory effect. This hypothesis seems coherent with results reported by Tomasino et al. (Tomasino et al., 2008), who compared effect of hand motor cortex stimulation towards different tasks: silent reading, frequency judgment and motor imagery. Authors found a stimulation effect only for the latter, which was not a true linguistic task (the linguistic level of processing-accessing the meaning of the word - is a prerequisite to perform the true task – imaging to perform the action and deciding whether it requires a hand rotation), and claimed that the primary motor cortex is involved only when an overt simulation of the action is required. According to our proposal, however, the reason why silent reading and frequency judgment were not modulated by the stimulation is that they do not entail a deep semantic processing (Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008). In line with Tomasino and collaborators’ hypothesis (Tomasino et al., 2008) we can suppose that, even in our case, the mechanism underlining the facilitatory effect is simulation: semantic comprehension of action verbs is accomplished by simulating the correspondent motor program; if the simulation process is temporarily blocked, the comprehension in turn is subjected to a delay. Probably M1 is the cerebral region that, among others (i.e. premotor cortex) supports this process of simulation, so the transient reduction of its excitability results in slower comprehension of action verbs.

With specific reference to the role played by the primary motor cortex in semantic processing, our findings support the hypothesis of a functional involvement. The use of rTMS gave us the opportunity to investigate this issue by inducing a transient reduction of cortical excitability and evaluating its impact on the semantic task: data obtained in this study suggest that "turning off" the motor area has a direct, causal effect on the response latencies, and this fact can be considered as a proof of the functional role of this area. Nevertheless, it is too early to claim that the primary motor cortex is *needed* in order to perform the task: the only way to make this claim should be to test the effect of the complete removal of this area on language comprehension. This happens in case of brain damage, but so far studies on patients with pathologies affecting motor system documented mostly a general preferential impairment of verbs, rather than a specific direct relationship between site of lesion and verb loss (Bak, 2010; Bak & Chandran, 2012). Hence, for the time being, it is more cautious to posit that the motor system *is* involved in a functional, and not epiphenomenal, way in language processing.

Finally, the laterality effect is another interesting result. Not only, indeed, the effects of rTMS are evident selectively for action verbs, but also selectively for left stimulation. RTs after right stimulation for concrete and abstract verbs, did not actually differ from each other, and furthermore, did not differ from RTs for abstract words following left stimulation. It means that, in right-handers, only the left primary motor cortex is involved in semantic comprehension, whereas the right one is not. The present findings extend those by Willems et al. (Willems, Hagoort, et al., 2010), who carried out an imaging study to compare premotor activity during action verb understanding in right-handers versus left-handers. The rationale is that if the action understanding process entails motor programs, than the processing of words describing actions that typically people perform with their dominant hand should activate the controlateral premotor cortex, which subserves the planning of the correspondent action.

The results confirmed this prediction, indicating that right-handers preferentially activated the left premotor cortex during lexical decision, whereas left-handers preferentially activated the right premotor cortex. Even if we did not compare right- vs left-handers, our results seem to support the hypothesis that, at least for right-handers, as happened for the premotor cortex, the primary motor cortex activated in language processing is that consistent with handedness. This can be considered as a further clue of the tight link between language and motor system.

4.6. CONCLUSIONS

The present study aimed at extending previous results about the relationship between language processing and motor system. According to the present findings, the primary motor cortex is involved in a functional manner during action verb comprehension and coherently with the handedness: in right-handers, only the left hand portion of the primary motor cortex has a role in the comprehension of verbs indicating hand actions. This outcome is relevant for different reasons. From a theoretical point of view, it deepens the knowledge about the nature and the origins of language, adding new data in support to the embodiment hypothesis; most importantly, it has some interesting concrete implications in the clinical practice. Aphasic patients often suffer from difficulties in retrieving the correct lexical item or in remembering the meaning of a specific word: the fact that the motor representations and the language representations are interwoven, even at the level of the primary motor cortex, opens new perspectives for the rehabilitation of such disabilities. As pointed out by Pulvermuller (Pulvermuller & Berthier, 2008), aphasia therapy should take advantage from this interplay by stimulating language through action. More specifically, authors proposed that, rather than training naming abilities in closed language settings, "It is advantageous to practise language in relevant action contexts" (*ibidem*).

Future research is needed to better clarify the role of the primary cortex in different conditions and processes not addressed by this study: different linguistic tasks should be used [with different degrees of semantic processing – i.e. passive hearing, as in Buccino's experiment (Buccino et al., 2005)]; the effect of laterality should be confirmed by including left-handers; the link between the content of the verb and the specific primary motor region involved (in our experiment: hand portion of M1 – hand-action verbs) should be tested by including other action verbs (i.e. foot-action verbs) and stimulating other cortical regions (foot portion of M1).

CHAPTER 5

EXPERIMENT 2: MOTOR SIMULATION IN A VIRTUAL ENVIRONMENT - A PILOT STUDY

The present chapter will describe the study performed in order answer to following question: is simulation triggered by a virtual movement?

The present study, thus, aimed at testing the contribution of virtual reality in the study of simulation mechanisms, which have been recognised to play a role during several linguistic processes. I used a virtual park, which participants had to explore as if they were running trough it, while performing a semantic judgment task. The effects of the virtual "run" have been compared with the watching of a video displaying runners. Electrical activity in the left primary motor cortex, and in the flexor pollicis brevis muscle of the right hand have been recorded. Results evidenced higher cortical activity during the virtual run.

5.1 INTRODUCTION: THE CONCEPT OF SIMULATION

Imagine being in a cinema, looking at an action movie. The protagonist keeps on running trough the streets and jumping from one car's roof to another, trying to escape from his enemies, who are running after to kill him. What happens in our brain in this moment? Beyond the primary perceptual areas, deputed to process the inputs (visual and auditory) from the environment, and the limbic system, activated by the emotional content of the scene, there are other neurons that fire in the same moment: the so called mirror neurons, that become active when both one makes an action and sees someone else making the same action. Thus, while looking at the scene above described, our premotor cortices, which seem to contain neurons with mirror-like features (Tettamanti et al., 2005), should be activated in the portion where foot actions are processed.

The phenomenon occurred in the cinema is often referred to as *motor resonance:* when I see someone doing something, his/her action produces in my brain a "resonance effect", as if I was doing that action myself. Motor resonance has been widely described in many experimental studies about action observation (Greenwald, 1970; James & Maouene, 2009; Jeannerod, 1994). Though**,** there are empirical data suggesting that motor resonance is triggered also by action-related linguistic stimuli (Gentilucci, 2003; Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Gentilucci & Gangitano, 1998; Glover, Rosenbaum, Graham, & Dixon, 2004; Tucker & Ellis, 2004; R. A. Zwaan & Taylor, 2006). This view is in agreement with the theoretical framework proposed by Barsalou (L.W. Barsalou, 1999): according to him, understanding a sentence passes through a language-induced mental simulation of the actions described in this sentence.

Typically, the simulation process is studied by coupling a linguistic stimulation and a motor output, so that the experimenter is able to observe if and how, by varying the linguistic content, the motor performance is modulated. The classical experimental paradigm is that used by Glenberg and Kaschak (A. M. Glenberg & Kaschak, 2002) (see paragraph chapter 1 section 1.3.2 for a detailed description), who first described the so-called Action Sentence Compatibility Effect (ACE). ACE predicts that processing a sentence depicting an action in one direction, performed with a specific body part, affects RTs if the response is provided by performing an action with the same body effector, but in the opposite direction (i.e. away vs towards the body).

In the last decade many data have been found that support the hypothesis of a simulation-based language comprehension, and the different experimental paradigms in which the effect emerged led the researchers to the conclusion that simulation is a quite robust mechanism. Frak et al. (Frak, Nazir, Goyette, Cohen, & Jeannerod, 2010) tested the effect of hand action-content words on grip force measured online during the language processing. Participants had to listen to words related or not to manual actions, while holding a cylinder with an integrated force sensor. The authors found that the amount of grip force varied depending on the type of words heard: in particular, only with hand action words, the force increased from about 100 msec after the onset of the word, peaked at 380 msec and fell abruptly after 400 msec from word presentation. The further observation that subjects, even when specifically interviewed, were unaware of this muscle tension changes was interpreted as a proof (at the peripheric level) of an automatic, unconscious motor simulation (at a central level).

Furthermore, simulation has been found to affect body posture (R.A. Zwaan, van der Stoep, Guadalupe, & Bouwmeester, 2012): authors, by means of a Wii balance board, evaluated the effect of the semantic content of the sentences on the posture changes, by analysing the growth curve of the movement trajectories. The data underlined that sentence content influenced the movement trajectory despite inconsistencies between described and actual movement.

Another cognitive domain that is affected by mental simulation is action prediction (Springer & Prinz, 2010). This experimental paradigm is inspired by the work of Graf et al (Graf et al., 2007) about the action prediction during occlusion: the basic assumption is that the last visible segment of action before occlusion is internally updated during occlusion and compared to the final, displayed position. Springer and collaborators were interested in investigating the effect of semantic content of linguistic stimuli on the action prediction of a displayed movement. For this purpose, they varied systematically the duration of the occlusion and the position of the target after the occlusion, and associated a prime word, with different action features. Results showed that action prediction performance was modulated by the kind of word (verb vs noun – experiment 1), by the type of verb (dynamic vs static – experiment 2), and by the action dynamics described by the verb ("fast" verbs vs "slow verbs – experiment 3).

Finally, there are evidences that simulation is influenced not only by semantics but also by grammar. Numerous studies reported that the conjugation in different verbal persons (mainly "you" vs "third person") led to a modulation of simulation effects in semantic processing (Bergen & Wheeler, 2005; Borreggine & Kaschak, 2006; Tseng & Bergen, 2005) and even in memory performance (Ditman, Brunye, Mahoney, & Taylor, 2010). More, Bergen et al. (Bergen & Wheeler, 2010) run an experiment designed to test the hypothesis that the grammatical form of the sentence impacts on the simulation process. They compared two grammatical forms of the same content sentence by modifying the verb tense, as follows:

(1) John is closing the drawer

(2) John has closed the drawer

The first form is called "progressive", because the action is *in fieri*, while the second one is called "perfect", and denotes an action already concluded in time. According to their predictions, only the form (1) triggers simulation, resulting in ACE effect, and this findings points out the role of grammatical information on mental simulation, with respect to semantic information: on one hand, content words tells the understanders what to simulate, and thus which brain regions are activated; on the other hand, grammatical constructions act on a second-order properties of simulation, by modulating how simulation is performed [i.g. simulation is localized in the portion of the sentence that specifies the type of motion - (R. A. Zwaan & Taylor, 2006)].

However, the direction of the effect of the simulation process is still unclear: does simulation help or interfere? The answer to this question is not obvious to date. In literature there are studies reporting opposing results. In some cases, the simulation process is deemed to produce faster RT, thereby a facilitation effect. Findings of this kind are common: beyond the classical, already cited experiment by Glenberg and Kaschak (2002), Myung (Myung, Blumstein, & Sedivy, 2006) found a facilitation in lexical decision about functionally similar objects (piano-typewriter); Rueschemeyer (Rueschemeyer, Lindemann, van Rooij, van Dam, & Bekkering, 2010) reported faster RTs when the action prepared to give the response matched that described by the linguistic stimulus (towards vs away from the body); Zwann (R. A. Zwaan & Taylor, 2006) and Taylor and Zwann (Taylor & Zwaan, 2008) got to similar findings by using action stimuli related to rotation (clockwise vs counterclockwise).

By opposite, the reverse situation is also described, characterised by an interference effect due to the match between the effector used to provide the answer and that involved in the action word or sentence processed. For example, Buccino (Buccino et al., 2005), using a go-no go task during a semantic decision task found that the match between effector employed to give the response (hand vs foot) and the effector ideally used to perform the action described by the verb (hand-related vs foot-related verbs) resulted in slower responses than in case of mismatch. Similarly, an interference occurred in the studies by Sato (Sato et al., 2008) and Glenberg et al. (A. M. Glenberg, Sato, & Cattaneo, 2008).

To account for these discrepancies different explanations have been proposed: the timing of the go-signal and the kind of linguistic task seem to play a role (Sato et al., 2008), in that the interference effect appears only in case of early delivery of go-signal (at the isolation point of the word or after 150 msec from its presentation) and with deeper semantic tasks (interference occurs with semantic judgment but not with lexical decision tasks). Furthermore, the temporal relations between the motor output and the linguistic stimulus have been proposed as a critical issue by Boulenger et al. (Boulenger et al., 2006): in their research, interference occurred when the two run in parallel, whereas facilitation occurred if the word preceded the movement. These findings have been further corroborated and extended by Nazir et al. (Nazir et al., 2008), whose data revealed that the interference become evident even when the words are presented delayed with respect to movement onset.

The following pilot experiment fits in this vein of research concerned to shed light on the process of simulation during language comprehension.

Thus, the aim of the present work is to extend the knowledge of the simulation process using a traditional paradigm but in a novel experimental setting: virtual reality. To reach this goal, a virtual environment has been implemented in which participants had to perform a semantic task (concreteness judgment) with or without concomitant real and “illusory” motor tasks achieved thanks to virtual reality technology. Since the paradigm used is replicated from Buccino et al. (Buccino et al., 2005), I expect to find out the same pattern of effects depending on the match-mismatch between action performed and action-verb presented. The innovation is due to the combination between electrophysiological measures (EEG, EMG) and the use of a virtual world that allows the user to get the impression of performing an action, even being completely steel. Thus the specific purpose of this pilot study is to test which action (the virtual one or the real one) triggers simulation; furthermore, I am interested in investigating which measure (the central one – EEG and/or the peripheral one – EMG) is affected by simulation. The predictions, for what concerns the peripheral level, are the following:

1. motor simulation is triggered by actual motion: if so, since participants use their hand to accomplish one of the task requirements, the comprehension of hand action verbs should result in slower RTs than that of foot or mouth action words;
2. motor simulation is triggered by virtual motion: if so, participants who virtually walk/run in the environment, should show worst performance for foot action verbs than for hand or mouth action verbs.

Accordingly, EEG waves recorded from M1 should be modulated by the content of the verb.

5.2 MATERIAL AND METHOD

5.2.1 Participants

12 volunteers, (7 males and 5 females; (age: range 28-45 years; mean: 38,25; st. dev.: 4.97; years of education: range 13-18; mean: 15.58; st. dev.: 1.97) have been recruited for the experiment thanks to public advertisement, and the following snowball effect. Participants were all native Italian speakers, and had normal or corrected-to-normal vision. None of them was aware of the specific purposes of the study. All of them signed an informed consent in order to join the experiment. The experimental procedure, and the specific consent form describing it, had been previously approved by the University Ethic Committee.

5.2.2 Stimuli

Twenty sentences were constructed for each type of verb: hand-action verb, foot-action verb, mouth-action verb and abstract verb. Some sentences were the same used by Buccino et al. (Buccino et al., 2005), some other were new: they are all listed in the Appendix (Table III). Sentences containing hand-action verbs, foot-action verbs or mouth-action verbs were considered concrete-content sentences, expressing a concrete action performed with different effectors (respectively hand, foot and mouth). On the other hand, sentences containing abstract verbs were considered abstract-content sentences, expressing typically intellectual or symbolic activities. Each sentence was repeated twice, so forty sentences for each type of verb were presented; thus, on the whole, the experiment consisted in 160 trials.

Sentence's syntactic structure was the following: verb + complement (article or preposition plus the appropriate object, for a total of three words). The verbs were all formed by three-syllables and were conjugated at the third person of the simple past tense, which requires the suffix –*va* to be added to the verb stem. The frequency of use of the verbs in the four types of sentences was kept similar, based on the available data about the frequency of use norms for the Italian language (De Mauro, Mancini, Vedovelli, & Voghera, 1993).

5.2.3 Virtual environment

The virtual environment (www.vrmmp.com) was lunched through the freeware software NeuroVr2 (www.neurovr2.org). It was designed as a park in a sunny day. When entering it, the participant started from a paved track, and the first-person point of view was set up as for an adult standing, ready to explore the park. Outside the track, the ground was completely covered by green grass, and enriched with trees and shrubs. In addition to natural items, a lot of artefacts, which one could typically encounter in a park, were shown: benches, streetlamps, bins. Furthermore, a pic-nic area and a playground area were displayed. No human being was present in the scene. In the Figure 1 a screenshot of the environment is represented.

Figure 1: a screenshot of the park

The paved track enclosed in a circle the two above mentioned areas, and then led to a hill where the edge of the environment was set up. From the top of the hill, on one side one could look down on the park, and on the other side could see the fog that indicated the end of the area where exploration was allowed.

All the objects, both natural or artefacts, were true solid entities that could not be passed through, such as in the real world: if the user accidentally or purposely banged into one of them, his or her walk was transiently stopped until he/she changed direction.

The interaction with the environment (when required, depending on the experimental condition – see below for a detailed description) was regulated by manipulating the left knob of the joypad (Xbox 360; see Figure 2, left side): moving it in the forward/ backward or left/right directions a coherent movement in the virtual scene was obtained. The key A was pressed to give the appropriate response when needed (see the next section for the procedure's description). The head-mounted display (Vuzix AV920: see Figure 2, right side), together with the connected headphones, allowed an immersive experience.

Figure 2: the Xbox 360 joypad (the red circle indicates the knob used to walk in the virtual environment, and the dart the key pressed to give the response) and the Vuzix AV920 Head-mounted Display.

5.2.4 Procedure

During the experimental protocol, the participants were welcomed in a quiet room by an experienced researcher. After reading and signing the informed consent the experimental task started. The virtual reality stuff included the pc, in which the virtual scene was displayed, and the interactive tools (joypad and HMD): all the stuff was arranged in front of the participant at a distance of approximately 50 cm.

Once the electrophysiological tools were arranged, the participants wore HMD and held the joypad, while the researcher lunched the practice session in order to let him/ her familiarise with the environment and the commands needed to interact with it. Afterwards, experimental session started. The main task was a semantic judgment of the sentences auditorily presented. In particular, participants were instructed to perform a go/no go task, in which they had to press a key on the joypad when the sentence heard was a concrete-content one, and refrain to press when the sentence heard was an abstract-content one. The go signal was a flash presented visually as a transient change of the light in the environment; it occurred always in coincidence with the end of the second syllable of the verb (e.g. corre'va sul prato), that is approximately 500-700 msec after the beginning of the sentence, depending on the verb's length. The response key was that identified by the red dart in Figure 2, and it was pressed with the right thumb.

In addition to the main task, the participant had to follow different instructions according to the experimental condition they belong to. There were two experimental conditions, which differed in terms degree of action: Run and Video conditions. In the RUN condition, the participants performed the main task (semantic comprehension) while exploring the park as if they were walking or running through it. The specific instructions underlined that they had to keep walking in whatever direction without stopping until the sentences ended out. The walk-like action inside the park was obtained by moving the joypad knob on the left (see Figure 2) with their left hand. This experimental condition required people to stand in front of the computer in order to assume a body position coherent with the virtual walk.

In the Video condition the participants seated in front of the computer and started the virtual experience as they were seated in a bench. In front of them, in the virtual environment, a television was arranged where a video of runners was displayed. The participants were instructed to look at the video carefully and to move the left knob when the direction of the motion in the video changed. This was done in order to pursue two goals: on one side, to make this condition comparable to the previous one in terms of attentional load, and to assign a task to the left hand; on the other side, to be sure that the video content was continuously processed by participants. This task was performed in concomitance with the main comprehension task. In sum, all the participants had to perform the main task (semantic comprehension) with the right hand (by pressing the key when needed) while performing a second, visuospatial task, with the left hand (by moving the knob).

After completing this step, that took about 13 minutes, the participants where asked to fulfil the *ITC–Sense of Presence Inventory (ITC-SOPI)* (Lessiter, Freeman, Keogh, & Davidoff, 2001), that measures the degree of presence experienced both *during* and *after* a virtual experience. It considers four dimensions: Physical space (a sense of physical placement in the mediated environment, and interaction with, and control over, parts of the mediated environment), Engagement (a tendency to feel psychologically involved and to enjoy the content), Ecological Validity (a tendency to perceive the mediated environment as life-like and real) and Negative effects (adverse physiological reactions).

5.3 DATA RECORDING AND ANALYSIS

Both electrophysiological and behavioural data were recorded. For recording neurophysiological data, a cap with 4 channels connected via bluetooth to a Pentium computer was used. Data from four electrodes were recorded, in the C1, C2, O1, and O2 positions. One more electrode was fixed at the ear lobe for reference. Every channel has been synchronously acquired at 2048 Hz and exported at a 1024 Hz sampling rate (1024 records per second, one record per 0.9765625 millisecond).

EEG signals needed to be extensively worked to remove ocular artifacts and blinks. Then the corrected matrixes could be computed to calculate means of the Alpha EEG (e.g., 8-13 Hz) bands, one per each channel recorded, through spectral analyses (Bagic, Knowlton, Rose, & Ebersole, 2011). Higher cortical activation is revealed by lower Alpha waves, and thus this needed to be considered in the computation and formula derivation.

The EMG latencies were used as a measure of the behavioural task. The raw electromyography (EMG raw) is a collection of positive and negative electrical signals; their frequency and amplitude give us information on the contraction or rest state of the muscle. Amplitude is measured in µV (micro-Volts). As the subject contracts the muscle, the number and amplitude of the lines increases; as the muscle relaxes, it decreases (Goodmurphy & Ovalle, 1999). It is generally considered the Root Mean Square (RMS) for rectifying the raw signal and converting it to an amplitude envelope (Blumenthal et al., 2005). In particular cases we can also be interested in frequency, related to muscle fatigue. There are a number of measures that can be extracted from this signal that depend on the muscle corresponding to the electrodes locations. For this study, we considered the RMS of EMG signals acquired by two patches placed on the flexor pollicis brevis muscle, which is involved in the button pressure (Figure 3); one additional reference patch was placed on the arm for reference.

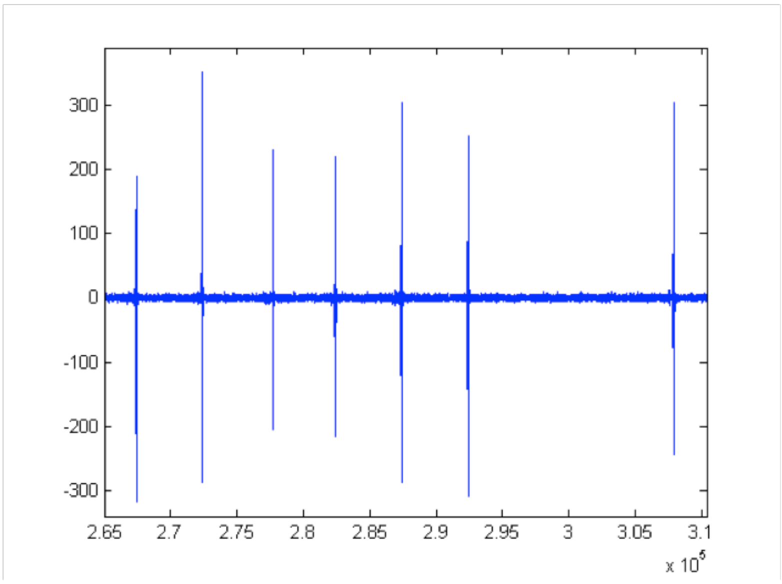

Figure 3: Some seconds (axis x = time) of Row EMG signal (axis Y= amplitude in µV) clearly showing 7 button pressures.

5.4 RESULTS

The first analysis was performed in order to verify the effects of the independent variables (Verb and Condition) towards the dependent variables (EMG-RTs and EEG signals). To do that, I run two Repeated Measures Anova with one factor between subjects with two levels (Condition: Run vs Video), and one factor within subjects with three levels (Verb: hand; foot and mouth). For one of the participants EEG signal was corrupted for high level of noise and so it was discarded from analyses. On the other hand, EMG-RTs were extracted for all the 12 participants.

Results underlined a specific effect of condition on the EEG signals [$F(1,9)= 6,648$; $p< 0.05$; $\eta^2= 0.43$], indicating that alpha waves were lower in the Run condition than in the Video Condition (Run= 0.002; Video= 0.003). No other effects appeared significant.

For what concern the EMG-RTs, neither the main effects [Verb: $F(2,20)= 0.573$; $p= 0.573$; Condition: $F(1,10)= 1,817$; $p= 0.2$], nor the interaction reached significance [$F(2,20)= 0.171$; $p< 0.844$].

Given the small sample size, I had a look of the descriptive data, which, even if not significant, appeared interesting for interpreting the data. Figure 4 represents the pattern of EEG alpha waves (left side) and of EMG-RTs (right side) in the two conditions, depending on the type of verb.

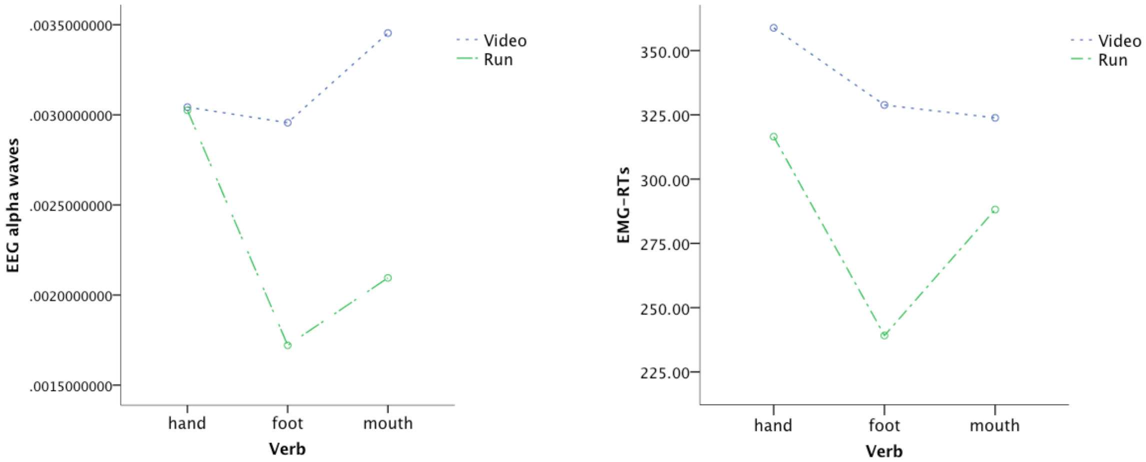

Figure 4: the effects of the Condition and of the Verb on the EEG and EMG-RTs measures.

Within the Run condition, there is a trend indicating that foot action-verbs elicited more cortical activity (lower levels of alpha waves), and accordingly, RTs for foot action verbs were faster than for hand and mouth action-verbs.
Second, the measures of presence have been taken into account, by entering the questionnaire's subscales as covariates in a Multivariate Analyses of Covariance (MANCOVA), with EEG waves and EMG-RTs as dependent variables and Condition as fixed factor. Results failed to yield any significant effect.

5.5 DISCUSSION

The present experiment aimed at extending the knowledge of simulation in language comprehension, by using a traditional paradigm but with novel experimental tools, thanks to virtual reality technology. For this purpose, I set up an experimental apparatus that included tools traditionally used in neuroscience (EEG, EMG) and other borrowed from positive and general psychology research (virtual reality). Combining together these different tools required a strong effort, mainly in the synchronisation process, that allowed the measures to be recorded simultaneously and aligned along the timeline. For these reasons a pilot study was necessary in order to test the feasibility of the setting.

Preliminary results suffered from the small sample size, but still underlined one interesting effect and some promising tendencies. The first is related to the difference between cortical activation recorded during Run condition and that recorded during Video condition: data revealed that the neural activity, in the primary motor cortex, was greater when participants run trough the virtual park that when they watched a video representing runners. It should be noticed that the two conditions were identical in terms of real movement: in both the cases the participants used their left hand to perform the secondary task in the virtual environment (the run vs the response to the attentional visual task), and their right hand to give the correct answer to the verbs. The only element that differed was the body position of the participant (i.e. seated in the Video condition and upright in the Run condition).

The difference observed in the cortical activity, thereby, cannot be attributed to differential involvement of the motor system in actions execution. If the real actions cannot account for this effect, one possible alternative explanation should take into consideration the virtual movement. As described in the Method section, participants in run condition, thanks to virtual reality immersive technology, got the impression to walk/run through the environment: it is possible that the virtual action activated the motor stream more than the mere observation of the same action performed by other people (as in the video). In this research I did not compare the virtual action with the correspondent real action, that is, a real run, so it is impossible to predict if the greater activation observed during the virtual run would be comparable with that observed in the real one. Though, the present findings agree with previous observations reported in literature: Maeda and coworkers (Maeda et al., 2002), investigated the impact of the subjective point of view during action observation on the M1 activation. In their work, participants viewed video of hand movements presented from two points of view: one compatible with the observer position, and one incompatible with it. Cortical excitability in the two conditions was measured by means of TMS stimulation and registration of MEP of hand muscles. Data underlined how, as already reported in other studies (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Strafella & Paus, 2000), the action observation induces changes in cortical excitability, but, more interestingly, MEP facilitation was higher when the observed action matched the observer's point of view.

It means that the observation-induced motor cortical modulation is modified by the action's orientation.
In this experimental setting the virtual action of run was observed by the participant as he was the actor, thus from the first person point of view: even if no body parts were visible in the environment, the subjective feeling of motion was ensured by the coherent change of the visual field in the virtual world. So I can suppose that the higher cortical activity found during the Run condition reflected the stronger involvement of the motor system due to the virtual action, compared to the observation of others' action. If so, the research allowed to point out the capabilities of virtual reality in recruiting cortical regions usually activated during real movement.
For what concerns the link between this cortical activity and the linguistic stimulus, present data do not permit to provide hypotheses grounded on observable statistical effects. In fact, based on the available measures, it is too early to speculate abut the presence of an interaction effect between the Condition and the type of verb; Nevertheless, the descriptive data suggest some interesting prompts about the direction of the trend that appears when considering that interaction.
Looking at the graph that represent the estimated means in the two conditions for the three types of verbs, several regularities between different measures (EEG and EMG-RTs) jump out: first of all, the different patterns of values for the two conditions. In the Video condition, both EEG and EMG-RTs did not change depending on the verb: values are very similar for hand, foot and mouth action-verbs. Second, the patterns of values for the Run condition: contrary to the Video condition, here a difference between type of verbs become evident; for both measures, values were lower for foot action-verbs than for hand and mouth action-verbs, indicating higher cortical activity and lower response time. So, descriptive data seem to indicate that during the virtual run, the cortical activity is higher mostly when verbs described foot action, and accordingly the participant answers faster to foot action-verbs than for other verbs.
Even if nothing can be said now about the presence and the direction of the effect, this trend, if confirmed, will add new data to the debate about the effect of the simulation process. According to Buccino et al. (Buccino et al., 2005) I would have expected an interference effect when the effector of the action and that involved in the action-verb matched: however, this prediction has not been confirmed, either if the real action or if

the virtual action is considered as a trigger for the simulation. In fact, if the real action would be the source of simulation, RTs for hand action-verbs would have been slower than for other verbs, and this is not the case (from both the statistical and descriptive point of view); if the virtual action would be efficient to induce simulation, the RTs for foot action-verbs would have been slower than for other verbs. This is not proved statistically, nor it is suggested by the descriptives. Actually, foot action-verbs, at least at a descriptive level, elicited faster responses. The reasons of this discrepancy can not be discussed in absence of strong results, but still the trend deserves attention.

Summarising, current results are limited to the higher cortical activity in the area of the primary motor cortex when a virtual run is performed; nevertheless, the fact that the descriptive observations go mutually in the same direction and are consistent with the statistical effect induces to think that a bigger sample size could help in clarifying the role of the verb and its interaction with the virtual experience.

5.6 CONCLUSIONS

The present experiment was designed with an innovative experimental apparatus in order to deepen the knowledge on the simulation process, taking advantage from virtual reality technology.

Unfortunately the small sample size affected the statistical power of the analyses and thus the current significant results are limited. However, one important finding arisen from this study is the impact of virtual reality in cognitive processing: a virtual motion can enhance cortical activity compared to the observation of the same motion.

This outcome is important for at least two reasons. First, it encourages further researches in the same direction oriented to continue the investigation of the link between action and action-related language. This line of research seems promising if we consider not only the statistically significant effect, but also the descriptives data and their interesting pattern. Second, it opens new paths towards the use of virtual reality in rehabilitation contexts: if the virtual motion acts on the brain similarly to the real one, this represents an opportunity for motor rehabilitation.

Surely, several further researches are needed to better understand the cognitive and motor representations triggered by a virtual experience, but this work can be considered as a first step in that direction.

CHAPTER 6

EXPERIMENT 3: MOTOR SIMULATION DURING FOREIGN LANGUAGE LEARNING

The present chapter will describe the study performed in order answer to following question: is the simulation process involved during verbal learning?

The present study, thus aimed at investigating the role of the simulation in second language learning. I used the same virtual environment described in experiment 2, that participants had to explore while learning 15 new verbs in Czech language. This condition was compared to a baseline, in which neither virtual, nor real movement were allowed. The number of verbs correctly remembered in a free recall task was computed, along with RTs and number of errors during a recognition task. Results underlined that simulation *per se* has no effect in verbal learning, but it is mediated by the features of the virtual experience.

6.1 INTRODUCTION

The link between action and language can be investigated also from the perspective of learning processes. In fact, the acquisition of language and, potentially, the rehabilitation of lexico-semantic deficits, can take advantage from coupling verbal and action information [see Macedonia, 2012 (Macedonia & von Kriegstein, 2012) for an extensive review]. Usually, verbal information refers to words or sentences, whereas action information is driven from gestures.

The impact of gestures on verbal memory has been studied since decades. Engelkamps and Krumnacker (Engelkamp & Zimmer, 1985), for example, demonstrated that the recall of action words or sentences is improved if, during learning, the subjects pantomime the correspondent action, compared to only the hearing/reading of the action items. This effect, which is often called “enactment effect”, not only impacts on the number of items correctly remembered, but also improves the accessibility of the items memorised, as it has been shown during recognition tasks (Masumoto et al., 2006).

The possibility to promote verbal learning by enriching the study phase with action information has been applied in a field where verbal memory has a crucial role: the foreign language learning (Taleghani-Nikazm, 2008). Several researches pointed out that gestures accompanying foreign language words increase their recall and prevent their decay (Kelly, McDevitt, & Esch, 2009; Macedonia, 2003; Tellier, 2008). Interestingly, even abstract words profit from the use of enactment, as it has been demonstrated by Macedonia and Knösche (Macedonia & Knösche, 2011). Authors asked participants to learn 32 sentences, made up of four words, only one of which was concrete (the subject), while the other being abstract. Critically, researchers manipulated the learning conditions: in one case, the items were presented audio-visually, in the other case they were enriched trough a gesture. The gestures coupled with abstract words were arbitrary and symbolic. During free and cued recall assessment the items, either concrete or abstract, learned in the enriched condition were remembered more than those in the mere audio-visual condition. This study confirmed that the performance in novel words learning can be enhanced by enriching the learning process with a motor act associated to the meaning of the word.

The reason why enacted items are better remembered and retained is a matter of debate in the scientific community. To explain the "enactment effect" different possible explanations have been proposed, that, though not being mutually exclusive, grasp different facets and highlight different perspectives.

Some author (Allen, 1995) refers to classical cognitive theories such as the principle of the depth of encoding (Craik & Tulving, 1975): accordingly, the deeper is the item's processing (i.e. in terms of semantic features), the more likely it will be recalled in the future, and the longer lasting the memory trace will be. Following this account, the items recall would benefit from enactment in the encoding phase since it deepen the level of processing.

Similarly, the Dual Code Theory by Paivio (Paivio, 1971; Paivio & Csapo, 1969) is sometimes invoked as a mechanism underlining this effect (Tellier, 2008): in this view, the items more efficiently remembered are those embedding not only verbal but also imagistic information. Gestures, from this perspective, provide the second "code" comparable to the imagistic one, in terms of motor trace.

The hypothesis of the motor trace is taken into account also by Macedonia et al. (Macedonia et al., 2011), to explain both concrete and abstract word learning during foreign language acquisition. According to the authors, "*performing a gesture when learning a word can fulfil two functions. First, it strengthens the connections to embodied features of the word that are contained in its semantic core representation. Second, in the case of abstract words such as adverbs, gesture constructs an arbitrary motor image from scratch that grounds abstract meaning in the learner's body*" (Macedonia & von Kriegstein, 2012).

Taken together, all these positions are based on the idea that the enactment's advantage is achieved trough an enrichment of the semantic representation.

However, another vein of research studied the effect of action on language processing, grounding its theoretical roots on the concept of simulation. According to Barsalou (L. W. Barsalou, 2008), "*simulation is the re-enactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind".* The effects of motor simulation have been widely investigated in several behavioural experiments, addressing different issues about the interplay between language and action in different linguistic processes (Bergen & Wheeler, 2010; Ditman et al., 2010; Frak et al., 2010; Papeo et al., 2011; Rueschemeyer et al., 2010; Springer & Prinz, 2010; Taylor & Zwaan, 2008; Tseng & Bergen, 2005; R. A. Zwaan & Taylor, 2006). The focus of these researches is either the action or the linguistic performance, or, in other cases, the crosstalk between the two: it should be noticed, though, that the results are sometimes contrasting (see a detailed description in the previous chapter) and then whether and in which conditions language and action mutually benefit or prevent is still a matter of debate.

Curiously, to my knowledge, only one paper aimed at applying the concept of simulation to the learning processes (Paulus et al., 2009). Authors were interested in investigating the role of motor simulation during verbal learning of functional object properties. In other words, they predict that if the acquisition of functional information about an object requires the mental simulation of its use, then an overt motor interference during the encoding phase, by blocking motor simulation, should affect the acquisition of the functional object knowledge. To test this hypothesis Paulus and collaborators constructed two sets of novel objects, half of which related to the action of hearing, and the other half to the action of smelling (both performed by manipulating the object with one hand). Participants saw the objects pictures and were instructed to verbally learn the functional properties by repeating them aloud. The learning settings were systematically varied according to four different interference conditions: *no interference*, *hand interference* (during the encoding phase participants had to squeeze a soft ball while performing a verbal learning task), *foot interference* (during the encoding phase participants had to press a soft ball with their feet while performing a verbal learning task), *attentional interference* (the task concomitant to the learning one was an auditory oddball target detection task).

As predicted, the performance in a subsequent test phase crucially decreased selectively in the hand condition, in which the actual motion performed during the learning phase interfered with spontaneous and covert motor simulation of the functional object knowledge.

However, this experiment taps into the learning processes referred to conceptual (i.e functional) information, and not into the language learning per se, as addressed in the previous described researches, using gestures enrichment.

Thus, the aim of the present work is to investigate the role of the motor simulation during foreign language learning. To reach this goal, an experimental setting has been implemented in which participants had to learn foreign action (hand or foot actions) and abstract verbs with or without concomitant real and "illusory" motor tasks achieved thanks to virtual reality technology. The prediction was the following: if the simulation of the action described by the verb is important for learning verb's meaning, then a concomitant action that involve the same effector of the verb should modulate its recall. More specifically, three scenarios can be predicted:

1. motor simulation is not involved: if so, the acquisition of action verbs is equal regardless the effector described;

2. motor simulation is involved and triggered by actual motion: if so, since participants use their hand to explore the virtual environment, the memorisation of hand action verbs should be modulated (the direction of the modulation is unpredictable based on available literature);

3. motor simulation is involved and triggered by virtual motion: if so, since participants virtually walk/run in the environment, the memorisation of the foot action verbs should be modulated.

6.2. MATERIAL AND METHOD

6.2.1 Participants

Forty-one volunteers, (15 males and 26 females; (age: range 19-49 years; mean: 33,17; st. dev.: 7,23; years of education: range 13-21; mean: 16,27; st. dev.: 2,33) have been recruited for the experiment thanks to public advertisement, and the following snowball effect. Participants were all native Italian speakers, and had normal or corrected-to-normal vision. Exclusions criteria included history of traumatic brain injury or neurological diseases. None of them was aware of the specific purposes of the study. They were informed that the one of them, whose performance would have resulted the best, will receive a coupon worth 50 euros. All of them signed an informed consent in order to join the experiment. The experimental procedure, and the specific consent form describing it, had been previously approved by the University Ethic Committee.

6.2.2 Stimuli

Fifteen verbs in Czech language were selected: five of them described actions performed with the hand, five actions performed with the foot/leg, and five intellectual or symbolic activities (the complete set of items is reported in Appendix - Table IV). The choice of Czech language was made because on one hand it is quite unknown in Italy (in order to avoid familiarity effects), and on the other hand its phonology is not too far comprehensible for Italian speakers. The three categories of verbs included items matched for length and frequency, according to the available database for spoken Italian (De Mauro et al., 1993). All the Czech verbs were audio-taped thanks to an online voice synthesiser; the correspondent Italian translations were recorded by a female human voice.

Each trial was composed by a Czech verb, followed by its Italian translation and by the repetition of the same Czech verb. So each trial was made up of three verbs, with 1 sec of delay in the between. The inter-trial delay was set up at 3 seconds. Figure 1 summarises trials composition and timing.

In each block the same trial was presented one time and the order of presentation was randomised. Five blocks have been construed in this way and randomly presented. Thus, on the whole, the task involved 75 trials.

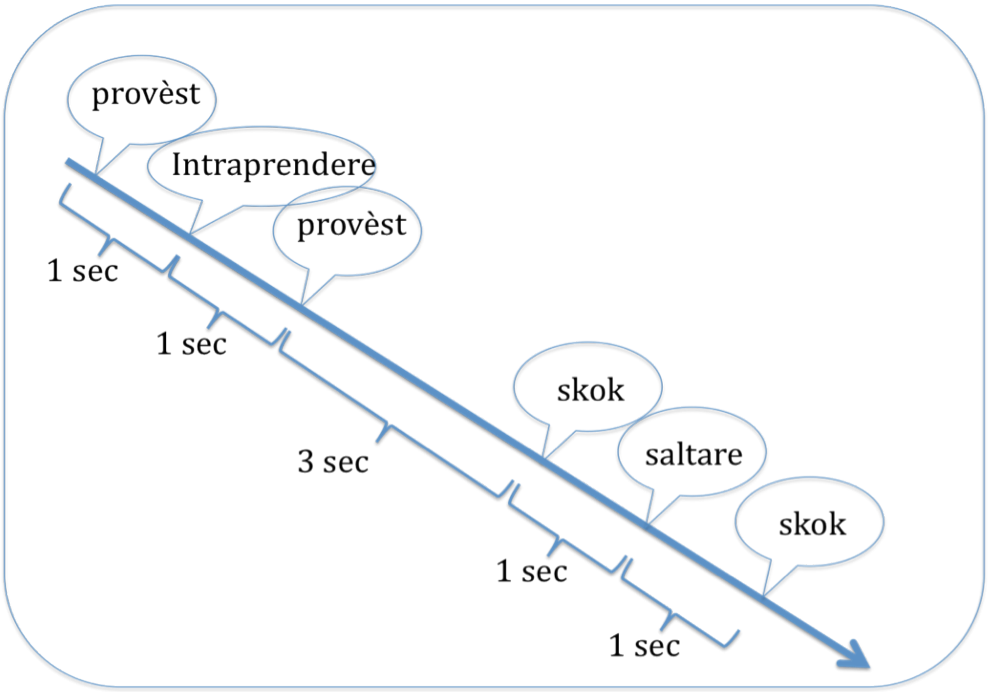

Figure 1: trials composition and timing

6.2.3 Virtual environment

The virtual environment (www.vrmmp.com) was lunched through the freeware software NeuroVr2 (www.neurovr2.org), and was the same used in the experiment 2.

The interaction with the environment (when required, depending on the experimental condition – see below for a detailed description) was regulated by manipulating the left knob of the joypad (Xbox 360; see Figure 2, left side): moving it in the forward/ backward or left/right directions a coherent movement in the virtual scene was obtained. The head-mounted display (Vuzix AV920: see Figure 2, right side), together with the connected headphones, allowed an immersive experience.

6.2.4 Procedure

Before attending the experimental session, volunteers were contacted by email and requested to fulfil online, at least one day before the laboratory session, the UsoImm77 questionnaire (Antonietti & Colombo, 1997). This questionnaire aims to investigate the spontaneous occurrence of visualisation and mental images in every day life activities.

During the experimental session, the participants were welcomed in a quiet room by an experienced researcher. After reading and signing the informed consent the experimental task started. The experimental stuff included the pc, in which the virtual scene was displayed, and the interactive tools (joypad and HMD): all the stuff was arranged in front of the participant at a distance of approximately 50 cm.

First of all the participant wore the HMD and held the joypad, while the researcher lunched the practice session in order to let him/her familiarise with the environment and the commands needed to interact with it. Afterwards, the experimental session started. The main task was a verbal learning of the verbs auditorily presented. In particular, participants were instructed to carefully hear the fifteen verbs in Czech and to try to remember as much items as possible. In addition to the main task, the participant had to follow different instructions according to the experimental condition they belong to. There were two experimental conditions: the Run and the Baseline conditions. In the Run condition, the participants performed the main task (verbal learning) while exploring the park as if they were walking or running through it. The specific instructions underlined that they had to keep walking in whatever direction without stopping until the verbs ended out. The walk-like action inside the park was obtained by moving the joypad knob on the left with their left hand. This experimental condition required people to stand in front of the computer in order to assume a body position coherent with the virtual walk.

In the Baseline condition the participants seated in front of the computer and started the virtual experience as they were seated in a bench. In front of them, the playground of the park was displayed. The participants were instructed to just relax and pay attention to the Czech verbs; no actions in the environment were required or allowed, with the only exception of the visual exploration of the scene (by turning around the head). This condition served as a baseline measure of the verbal learning.

After completing study phase, that took about 12 minutes, the participants where asked to perform a free recall task: the experimenter presented, one at the time, the fifteen Czech verbs auditorily and the participants had to provide orally the correspondent Italian translation. The number of verbs correctly remembered was counted. Immediately after the free recall task, a recognition task was performed. The participants seated in front of another computer screen connected to a response box. They were instructed to listen to the Czech verbs and to select, as quickly as possible, one of the two possible translations written on the left and right side of the screen, by pressing the correspondent left or right button of the button box (with both the hands). The correct response was equally presented on the left and on the right side of the screen. Each Czech verb was presented three times in random order and the correct translation was always coupled with a wrong, but plausible, translation (i.e. the translation of another presented verb). The reaction times were recorded.

At the end of the memory tasks, the participants fulfilled the *ITC–Sense of Presence Inventory (ITC-SOPI)* (Lessiter et al., 2001), which measures the degree of presence experienced both *during* and *after* a virtual experience. It considers four dimensions: Physical space (a sense of physical placement in the mediated environment, and interaction with, and control over, parts of the mediated environment), Engagement (a tendency to feel psychologically involved and to enjoy the content), Ecological Validity (a tendency to perceive the mediated environment as life-like and real) and Negative effects (adverse physiological reactions).

6.3 RESULTS

First of all, I was interested in testing the impact of the different virtual experiences towards the dependent variables (number of verbs correctly remembered in the free recall task, RTs of verbs correctly recognized and number of errors in the recognition task). For this purpose, a series of Repeated Measures Anova were run, with one variable within subjects with three levels (Verb: hand – foot – abstract), and one variable between subjects with two levels (Condition: baseline – run). Results highlighted that for what concerned the number of items recalled, there was an effect of the type of Verb [$F(2,78)= 27.261$; $p< 0.001$; $\eta^2= 0.41$], but not of the Condition [$F(1,739)= 0.618$; $p= 0.436$]. Contrasts computed on the variable Verb demonstrated that abstract verbs were more difficult to remember than hand or foot action verbs [$F(1,39)= 66.751$; $p< 0.001$; $\eta^2= 0.631$], but hand action-verbs and foot action-verbs did not differ [$F(1,39)= 0.952$; $p= 0.335$]. Furthermore, the effect of the type of Verb did not change depending on the Condition [Verb X Condition: $F(2,78)= 0.703$; $p= 0.498$].

With respect to the recognition task, the number of errors was not influenced by the type of Verb [$F(2,78)= 2.035$; $p= 0.14$], nor by the Condition [$F(1,39)= 1,95$; $p= 0.17$], nor by the interaction between the two [$F(2,78)= 0.79$; $p= 0.46$]; in agreement with the pattern found for the free recall measure, RTs were influenced by the Verb [$F(2,78)= 6.52$; $p< 0.05$; $\eta^2= 0.14$], but not by the Condition [$F(1,39)= 2,79$; $p= 0.1$], nor by the interaction Verb X Condition [$F(2,78)= 0.13$; $p= 0.71$]. Contrasts showed that RTs for abstract verb were slower than for the other type of verbs [$F(1,39)= 15.061$; $p< 0.001$; $\eta^2= 0.28$], that are similar to each other [$F(1,39)= 0.59$; $p= 0.449$].

Afterwards, the scores of the questionnaires have been taken into account.

First, I computed a MANCOVA, using the responses (numbers of errors, response time and free recall performance) as dependent variables, the Condition (baseline vs. run) as a fixed factor, and the sub-scales of ITC-SOPI questionnaire as covariates.

The general model was significant for number of errors in recognizing the correct translation of hand-related verbs [$F(5, 35)= 6.72$; $p< 0.001$; $\eta^2= 0.49$; $R^2= 0.49$]: participants in the baseline condition tended to commit less errors ($M = 2.10$; $SD = 1.59$) than those in the run condition ($M = 3.29$; $SD = 2.41$).

As covariates, the sub-scale *Engagement* [$F(5,35)= 6.37$; $p< 0.05$; $\eta^2= 0.15$] and *Negative Effects* [$F(5,35)= 17.15$; $p< 0.05$; $\eta^2= 0.33$] appear to have contributed to this difference.

Data highlighted how the *Engagement* sub-scale had a negative relationship with this dependent variable ($B= -1.68$; $t= -2.52$; $p< 0.05$) and, hence, the higher the level of *Engage* the lower the mistake rate. The opposite was true for the *Negative Effects* sub-scale: higher scores in this sub-scale was positively related to higher number of errors (B= 1.46; t= 4.14; p< 0.001).

Examining the influence of specific covariates on our independent variable, it was possible to highlight another interesting effect. Considering the number of errors in translating foot-related verbs - the sub-scale Eco-Valid had a significant influence [F(5, 35)= 5.17; p< 0.05; η^2= 0.13). This sub-scale had a negative relationship with the dependent variable (B= -1.10; t= -2.27; p< 0.05), hence the higher the *Ecological Validity* score, the lower the error rate in recognizing the correct translation of foot related verbs. Interestingly, mean estimates[3] predicted by the effect of this subscale (Baseline = 2.091; Run = 1.866) are in the opposite direction with respect to the observed sample means (Baseline = 1.8; Run = 2.14) (see Figure 2).

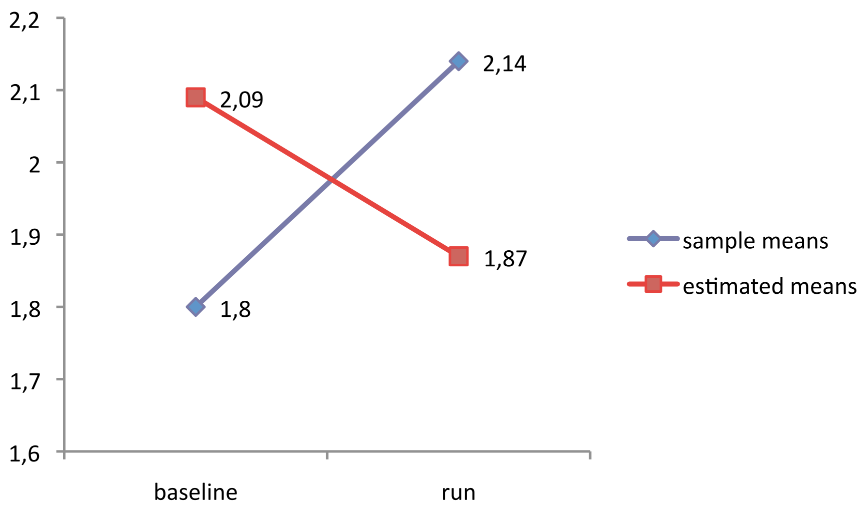

Figure 2: the effect of the scale Ecological Validity[3] for the number of recognition errors related to foot action-verbs. The group means estimated by the model go in the opposite direction with respect to those observed in the sample.

Second, the same analysis was applied to the UsoImm 77 questionnaire, using the same dependent variables, the same fixed factor and, as covariate, the global score of the questionnaire. Results revealed no significant effects for any considered variable, thus indicating that the individual tendency to use imagery did not influence the task.

[3] covariate Ecological Validity is evaluated in the model at the following value: 3.2683

6.4 DISCUSSION

The present study aimed at investigating the role of motor simulation during second language learning. To achieve this goal, I used a virtual environment in which participants, while learning Czech verbs, had to move as if they where running by acting on a knob with their left hand. This procedure allowed to obtain two kinds of action: one real (the movement of the hand on the knob), and one virtual (the virtual movement of the feet, necessary to run). Comparing the linguistic performance (in terms of learning) in this condition with that in the baseline condition (without movements), I have been able to point out if simulation is involved in this process, and which movement triggers it.

Looking at the experiment's results, it is quite clear that, on the whole, the simulation process does not seem to play a role during second language learning: in fact, the number of items correctly recalled did not vary across conditions, but only depending on the type of verb: the abstract verbs are more difficult to remember than the concrete ones. This finding is not surprising, since the cognitive advantage of concrete words over abstract words has been recognised in several memory and language tasks (Nelson & Schreiber, 1992; Paivio, Walsh, & Bons, 1994).

Though, the fact that hand-action verbs and foot action verbs did not differ from each other, and moreover that the effect of the verb type was not different depending on the conditions, seem to indicate that both the actions, real and virtual, did not affect the learning of the verbs that describe actions performed with the same or different effector. Coherently, during recognition task, the same pattern of effects became evident: the words previously better retained (hand and foot action verbs) were more quickly recognised, and the opposite was true for the words less remembered (abstract verbs). The number of errors in the recognition task, on the contrary, did not appear to be influenced by any considered variable: one possible explanation is that error rate did not rely on the learning process but on random factors.

The fact that simulation apparently is not involved in verbal learning is a novel finding. Data in literature reported an advantage in terms of language learning due to the coupling of words or sentences with gestures (Kelly et al., 2009; Macedonia & von

Kriegstein, 2012; Tellier, 2008). However, the action enrichment achieved by using gestures and that obtained by using the typical paradigm employed to test simulation differ in very basic ways: in one case the learner pairs a lexical item with a univocal pattern of movements, and the couple action + word is repeated over and over during the study phase; in the second case, a specific movement (virtual or real – in this study respectively the run and the manipulation of the knob) is performed for all the duration of the study phase with one specific effector, that matches or not the one described by the verb: there is not a specific combination between motion and semantics, but only a generic sharing/not sharing of the effector. It is easily conceivable that the gesture paradigm is better suited to promote the grounding of the meaning in the learner's body experience, whereas the mere use of the same vs different effector is not enough to establish a link between the lexical item and the action.

However, the involvement of simulation is reported in verbal learning task, when the matter of learning is conceptual knowledge (Paulus et al., 2009): in this study, probably, learners were explicitly requested to pay attention to the functional use of the objects, thus it is possible that the specific instructions induced to imagine the possible use of that object. In this case probably a process of imagery is activated more likely than a process of simulation, which relies on different cerebral networks (Willems, Toni, et al., 2010).

The absence of simulation in second language learning, as opposed to its well-established involvement in other linguistic tasks, such as comprehension (Ditman et al., 2010; Frak et al., 2010; Tseng & Bergen, 2005; R. A. Zwaan & Taylor, 2006), seems to posit that simulation is a quite "automatic" mechanism, activated during processes that operate online, sometimes guided by the context or the attentional focus (Bergen & Wheeler, 2010; Taylor & Zwaan, 2008), but never penetrated by conscious strategies. In this light, foreign language learning is a typical process in which individual strategies have a strong impact: in fact, participants spontaneously told the experimenter the tricks used in order to recall as much verbs as possible in the final test.

For this reason, the absence of a simulation effect in a language learning task does not rule out the involvement of the motor system in this linguistic process.

The second, and somehow surprising results is the effects of simulation in the recognition task. As discussed for the recall, the recognition measures as well do not seem to be influenced by the condition of learning (with or without virtual/real movement), but more interestingly, some effect arises from the contribution of the presence components, as assessed by the ITC-Sopi questionnaire.

In particular, the number of hand action verbs errors in the recognition task seems to be predicted globally by the set of subscales of the questionnaire, with *Engagement* and *Negative effects* being the most important predictors: the higher the level of *Negative effects*, the higher the number of errors; by opposite, the *Engagement level* promotes the decrease of hand action - verbs errors. This result could be interpreted within the simulation framework: hand action-verbs are more easily recognised if acquired without interference movement (baseline condition), when the learner experienced a high level of *Engagement* and low levels of *Negative Effects,* conditions that are likely to allow simulation.

Even more interesting is the effect on the number errors for foot action-verbs: this measure appeared to be influenced specifically by the *Ecological Validity*, that is the tendency to recognise the environment as real-like: when this index is higher, the errors decreased; more, the impact of *Ecological Validity,* when controlling for the other subscales, is predicted to yield less errors in the Run condition than in the Baseline condition. This effect as well is compatible with simulation: in the Run condition learners perform a virtual motion with their feet, and this action is simulated exactly at the time of the lexical access. Thus, the more the learner has interpreted the environment as real, the more the virtual action has been effective on the cognitive representation of the verb, the more he simulates the action during the recognition: the foot action simulation in turn facilitates the lexical access to the verbs that share the same effector.

Notice that this view is in perfect agreement with the Riva's proposal (G. Riva & Mantovani, 2012): as better described in paragraph 3.2, presence is viewed as an intuitive and simulative process, useful to judge the consequence of an action.

The present data support and extend this vision, by demonstrating that presence and simulation, independently measured, interact during language processing.

6.5 CONCLUSIONS

The aim of the experiment was to extend the knowledge about the mechanism of simulation. In particular, I was interested in testing the occurrence of this process during linguistic tasks the simulation has never been applied to so far: second language learning. The first important finding is that the simulation *per se* is not sufficient to establish a tie between words and action during learning, thereby resulting in null effect with respect to the number of items recalled. According to these results, it should be admitted that in order to support foreign language learning the best choice is to enrich the linguistic material with gestures (Macedonia & von Kriegstein, 2012).

Nevertheless, and maybe more interestingly, the used paradigm allowed to underline a novel finding: the simulation can be mediated by other perceptual, cognitive and emotional processes induced by the context. In this perspective, the use of virtual reality gave me the opportunity to point out how experience factors, mainly related to the concept of presence, can promote or interfere with the simulation process that occurs even after the virtual experience, as evidenced during the recognition task.

This result tells us at least two things: on one hand, it makes clear that simulation can take place when the lexical item must be accessed after being learned; on the other hand, it pinpoints that the occurrence of simulation during this process is mediated in different ways by different components of presence, which, on the whole, appears to be involved. The latter observation opens interesting questions to be solved with future researches: is it possible to modify the virtual environment in order to fit the parameters that allow simulation (according to the present findings: *Negative Effects*, *Ecological Validity*, and *Engagement*)? What happens when the environment is "optimized" in terms of presence: could the simulation speed up the time to access the word as well (in the present study RTs do not appear to be influenced)?

Since in the present research the virtual environment was very basic and the virtual experience allowed a low level of interaction, it is possible to guess that implementing a virtual world that induces higher levels of presence researchers can attempt to answer these questions.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUDING REMARKS

This research project was designed to investigate the relationships between language and motor system. Moreover, a further aim was to test the usability and feasibility of virtual reality as a new tool for addressing the open questions or introducing new ones. As a whole, the project yielded interesting results, though some issues have not been solved, and are still waiting for additional investigations.

One important and novel finding is the functional role of the primary motor cortex during language comprehension (exp. 1). Several studies in literature by applying single pulse TMS over the motor areas, demonstrated a modulation of the cortical excitability in the primary and premotor areas during linguistic tasks involving action-related stimuli (Fadiga et al., 2002; Fourkas et al., 2006; Oliveri et al., 2004; Pulvermuller et al., 2005); however, the kind of the involvement of M1 was still matter of debate between supporters of the "epiphenomenal" hypothesis, and the proponents of the "necessity" hypothesis. In fact, the single pulse TMS paradigm is barely suited to disentangle the issue: one could vary the time of the stimulation with respect to the onset of the word and check if differential timings affect differently the MEP, presuming that the earlier is the modulation the more likely the area has an active role in the process, the later the modulation occurs the more likely the role is thought to be ancillary (Papeo et al., 2009). This procedure, yet, infers the role of the motor area during linguistic tasks starting from a motor measure: in my work, by opposite, I chose to examine the role of M1 directly by measuring the efficiency of the linguistic task; furthermore, I applied off-line low frequency rTMS, in order to induce the so-called *virtual lesion*, and test the effect of the temporary reduction of the cortical excitability towards the language performance. In this way, I have been able to point out that the involvement of the primary motor cortex during action-verbs comprehension is not epiphenomenal, nor necessary: according to the present findings it seems more cautious to state that M1 has a *functional* role in semantics: its activation is required to correctly and efficiently perform a semantic task, but it is too early to say that M1 is strictly needed in this process. Only patient studies, examining the effects of the lack of this area, could provide evidence of such kind of involvement.

The fact that M1 is not only deputed to send to the muscles the input to execute an action is confirmed by the findings obtained in the experiment 2: in this case a virtual environment has been used to test the effect of virtual compared to real action and action observation in a similar semantic judgment task. In this experiment, with different methodologies, I extended the knowledge about the activity of M1 during non-motor task. Previous studies described the activation of different portions of M1 during action verbs processing (Pulvermuller et al., 2000); other researches reported an involvement of M1 during action observation (Strafella & Paus, 2000); this work, thanks to the capabilities of virtual reality, allowed to recognise a different level of activation depending on the motor information the subject is exposed to. In particular, I found that a virtual action, performed staying almost steel, is able to induce higher cortical activity in M1 the observation of the same action but performed by other people. On e possible interpretation of this effect refers to the actor perspective (Maeda et al., 2002): if the action I see is executed from a perspective compatible with the first person point of view the brain activity is greater than if I see an action executed starting from an orientation typical of other person's point of view. This result makes sense if thought in the framework of the Hebbian learning: as Cameirao argued " … the first person view should provide the most effective drive onto these multi-modal populations of neurons [*mirror neurons*] simply because this is the perspective that the system is most frequently exposed to".

The consequences of this interesting effect could be the object of future researches, that would give important contributions to the study of the cognitive processes and also of the applicative capabilities (rehabilitation).

The second main issue that the project was committed to was the investigation of the multiple facets of the simulation mechanism. Simulation is a very widespread phenomenon: it occurs during simple action observation (and in this case if often called motor resonance) (Greenwald, 1970; James & Maouene, 2009; Jeannerod, 1994), as well as during various types of linguistic tasks (see Barsalou, 2008 for a review).

In the present work two main research questions underwent scientific investigation:

1. is the simulation process differently triggered inside a virtual environment, while performing a virtual action, compared to the observation of others' action?
2. is the process of simulation involved in language learning?

The first question was addressed in the experiment 2, which was a pilot study aiming at testing the implementation of the simulation paradigm inside the virtual world. Unfortunately the small sample size affected the statistical power of the data, an then nothing can be said about the interaction between motor information available (acting vs observing) and the type of verb. Though, an interesting trend has been detected in the pattern of RTs and EEG data, indicating that within the virtual run condition foot action-verbs seem to be processed faster and to be associated to greater M1 activity.

Further experiments are needed to confirm this trend and to interpret the direction of the interaction.

The second question has been the object of the third experiment, in which the same virtual environment was used to test the effect of the simulation toward the learning of new words in a foreign language. Results underlined that the match/mismatch between the effector used to execute a virtual/real action and that involved in the action described by the verb did not affect the number of items learned, nor the number of errors or the RTs during a recognition task. Apparently, the process of simulation either did not take place or did not matter in the learning process.

The resolution of this doubt arose from the analysis of the presence questionnaire ITC-Sopi: some subscales of the questionnaire appeared to influence some of the measures of learning, thus mediating the effect of simulation. Again, the real movement and the virtual one behaved differently: the number of errors in recognising the correct translation for foot action-verbs appeared to be influenced specifically by the *Ecological Validity*, that is the tendency to recognise the environment as real-like. When this index is higher, the errors decreased; even more interestingly, the impact of *Ecological Validity,* when controlling for the other subscales, is predicted to yield less errors in the Run condition than in the Baseline condition. On the other side, the number of errors in translating hand action-verbs benefitted from high scores in *Engagement* and low levels of *Negative Effects,* but the lower rate of errors is predicted when there is no interference effect, that is in the baseline condition.

Summarising, the study 3 added data in favour of the hypothesis that the virtual world is able to trigger simulation (and the finding of a higher cortical activity during virtual run in the study 2 confirm these data), but the simulation is not sufficient to promote verbal learning; instead its contribution appears during the lexical access (recognition task). At this point I can suppose that the condition of acquisition undergo a process of simulation, that is more efficient if the virtual environment met some features that enhanced the sense of presence.

Taken together, the findings driven from this project highlighted some interesting points: the involvement of the primary motor cortex in language comprehension and virtual action processing testifies the complex role of this area not only in basic motor processes but also in higher cognitive activities; the simulation in language tasks is a multifaceted mechanism whose role is not yet completely understood; simulation and presence are confirmed to be strictly linked, and sometimes work in concert to increase the process efficiency (learned words recognition); the virtual reality system has promising capabilities in the study of embodiment, since it resulted effective in modulating cortical activity.

In conclusion, the issues addressed in this project, being only partially elucidated, deserve further investigation, and virtual reality can be taken into account as a complementary tool for the study of action and language within the theoretical framework of the Embodied Cognition.

APPENDIX

Stimulus	Translation	Verb type	Frequency	Syllable Length	Letters Length
afferrare	to catch	concrete	126	4	9
abbottonare	to button	concrete	5	5	11
accarezzare	to caress	concrete	58	5	11
accartocciare	to scrunch up	concrete	3	5	13
appallottolare	to crumple	concrete	1	6	14
annodare	to knot	concrete	12	4	8
applaudire	to clap	concrete	65	4	10
colorare	to color	concrete	29	4	8
dipingere	to paint	concrete	134	4	9
disegnare	to draw	concrete	190	4	9
firmare	to sign	concrete	407	3	7
impugnare	to clasp	concrete	46	4	9
intagliare	to carve	concrete	2	4	10
pennellare	to brush	concrete	3	4	10
pettinare	to comb	concrete	11	4	9
pugnalare	to stab	concrete	6	4	9
sbottonare	to unbutton	concrete	2	4	10
sbucciare	to peel	concrete	43	3	9
schiaffeggiare	to slap	concrete	6	4	14
sfogliare	to flip	concrete	44	3	9
slacciare	to untie	concrete	6	3	9
spalmare	to spread	concrete	20	3	8
stappare	to uncork	concrete	4	3	8
strappare	to tear out	concrete	163	3	9

Table I: list of items describing hand actions, included in the condition: concrete verbs (experiment 1)

Stimulus	Translation	Verb type	Frequency	Syllable Length	Letters Length
odiare	to hate	abstract	115	3	6
dirimere	to settle	abstract	4	4	8
stimare	to estimate	abstract	54	3	7
deprecare	to deprecate	abstract	3	4	9
infamare	to defame	abstract	2	4	8
propendere	to be inclined	abstract	11	4	10
rassegnare	to resign	abstract	64	4	10
terrorizzare	to terrify	abstract	26	5	12
fallire	to fail	abstract	121	3	7
apprezzare	to appreciate	abstract	163	4	10
immaginare	to imagine	abstract	353	5	10
scordare	to forget	abstract	42	3	8
preventivare	to budget	abstract	3	5	12
travisare	to misrepresent	abstract	4	4	9
perpetrare	to perpetrate	abstract	10	4	10
precorrere	to anticipate	abstract	6	4	10
calunniare	to slander	abstract	1	4	10
motivare	to motivate	abstract	44	4	8
tergiversare	to shilly-shally	abstract	9	5	12
intraprendere	to undertake	abstract	54	5	13
precludere	to preclude	abstract	8	4	10
semplificare	to simplify	abstract	22	5	12
sublimare	to sublime	abstract	3	4	9
sopportare	to tolerate	abstract	154	4	10

Table II: list of items describing intellectual or symbolic activities, included in the condition: abstract verbs (experiment 1)

	HAND ACTION VERB	FOOT ACTION-VERB	MOUTH ACTION-VERB	ABSTRACT VERBS
1	cuciva la gonna (He) sewed the skirt	calciava la palla (He) kicked the ball	baciava la guancia (He) kissed the cheek	amava la moglie (He) loved his wife
2	girava la chiave (He) turned the key	calciava la porta (He) kicked the door	baciava la mamma (He) kissed the mom	amava la patria (He) loved his country
3	lavava i vetri (He) washed the windows	calciava la sedia (He) kicked the chair	leccava il francobollo (He) licked the stamp	gradiva la mela (He) loved the apple
4	prendeva la tazza (He) took the cup	correva nel parco (He) run in the park	leccava il gelato (He) licked the ice-cream	odiava il mare (He) hated the sea
5	scriveva il tema (He) wrote the essay	correva sul prato (He) run over the grass	mordeva il pollo (He) bit the chicken	pativa il caldo (He) suffered from the heat
6	sfilava il filo (He) paraded the thread	marciava sul posto (He) marched on the place	mordeva la pagnotta (He) bit the bread	perdeval la guerra (He) lost the war
7	sfiogliava il libro (He) turned over the pages of the book	pestava l'erba (He) trod on the grass	succhiava il latte (He) sucked the milk	perdeva la pazienza (He) lost his patience
8	spalmava la crema (He) spread the cream	pestava la corda (He) trod on the rope	succhiava il pollice (He) sucked the thumb	sapeva la poesia (He) learned the poem
9	spezzava il pane (He) broke the bread	pestava le foglie (He) trod on the leaves	baciava la guancia (He) kissed the cheek	scordava il nome (He) forgot the name
10	stringeva la mano (He) shook the hand	saltava il fosso (He) jumped the ditch	baciava la mamma (He) kissed the mom	scordava la data (He) forgot the date
11	suonava il piano (He) played the piano	saltava il muro (He) jumped the wall	leccava il francobollo (He) licked the stamp	serbava l'odio (He) kept the hate
12	svitava il tappo (He) unscrewed the stopper	saltava la corda (He) jumped the rope	leccava il gelato (He) licked the ice-cream	soffriva il freddo (He) suffered from the cold
13	tagliava la carne (He) cut the meat	marciava sul posto (He) marched on the place	mordeva il pollo (He) bit the chicken	temeva il buio (He) feared the dark
14	tagliava la stoffa (He) cut the cloth	calciava la palla (He) kicked the ball	mordeva la pagnotta (He) bit the bread	temeva la pena (He) feared the penalty
15	timbrava la busta (He) stamped the envelope	calciava la porta (He) kicked the door	succhiava il latte (He) sucked the milk	vinceva la gara (He) won the competition
16	stappava la bottiglia (He) uncorked the bottle	pestava l'erba (He) trod on the grass	succhiava il pollice (He) sucked the thumb	soffriva il freddo (He) suffered from the cold
17	firmava il contratto (He) signed the contract	pestava le foglie (He) trod on the leaves	leccava il francobollo (He) licked the stamp	serbava l'odio (He) kept the hate
18	lavava i vetri (He) washed the windows	correva nel parco (He) run in the park	mordeva il pollo (He) bit the chicken	gradiva la mela (He) loved the apple
19	spezzava il pane (He) broke the bread	correva sul prato (He) run over the grass	baciava la guancia (He) kissed the cheek	sapeva la poesia (He) learned the poem
20	svitava il tappo (He) unscrewed the stopper	saltava il muro (He) jumped the wall	succhiava il pollice (He) sucked the thumb	odiava il mare (He) hated the sea

Table III: items (and their English translation) used in the experiment 2. Note that each items was repeated twice, for a total of 160 items presented in a single block.

	CZECH VERB	ITALIAN TRANSLATION	VERB TYPE
1	kopat	calciare	foot action-verb
2	skok	saltare	foot action-verb
3	bruslit	pattinare	foot action-verb
4	pochod	marciare	foot action-verb
5	bezet za	rincorrere	foot action-verb
6	kura	sbucciare	hand action-verb
7	prohlizet	sfogliare	hand action-verb
8	odzanotkovack	stappare	hand action-verb
9	kreslit	disegnare	hand action-verb
10	hreben	pettinare	hand action-verb
11	provést	intraprendere	abstract
12	zapomenout	scordare	abstract
13	usadìt	dirimere	abstract
14	ocenovat	apprezzare	abstract
15	oprit	propendere	abstract

Table IV: the complete set of items included in the experiment 3.

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