From Gesture to Speech

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One of the major problems concerning the evolution of human language is to understand how sounds became associated to meaningful gestures. It has been proposed that the circuit controlling gestures and speech evolved from a circuit involved in the control of arm and mouth movements related to ingestion. This circuit contributed to the evolution of spoken language, moving from a system of communication based on arm gestures. The discovery of the mirror neurons has provided strong support for the gestural theory of speech origin because they offer a natural substrate for the embodiment of language and create a direct link between sender and receiver of a message. Behavioural studies indicate that manual gestures are linked to mouth movements used for syllable emission. Grasping with the hand selectively affected movement of inner or outer parts of the mouth according to syllable pronunciation and hand postures, in addition to hand actions, influenced the control of mouth grasp and vocalization. Gestures and words are also related to each other. It was found that when producing communicative gestures (emblems) the intention to interact directly with a conspecific was transferred from gestures to words, inducing modification in voice parameters. Transfer effects of the meaning of representational gestures were found on both vocalizations and meaningful words. It has been concluded that the results of our studies suggest the existence of a system relating gesture to vocalization which was precursor of a more general system reciprocally relating gesture to word.

Keywords: Broca's area; gesture; human kinematics; mirror neurons; voice spectra; word

1. Introduction

The term gesture is used for describing social interactions involving especially movements of human hands and arms. Kendon (1982, 1988) classifies gestures along a continuum of 'linguisticity', observing that from gesticulation to sign languages the obligatory presence of speech declines, the presence of semantic properties increases and the idiosyncratic gestures are replaced by socially regulated signs. In other words, the formalized, linguistic component of the expression present in speech is replaced by signs going from gesculation to sign

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languages. Hand and arm movements are distinguished, namely gesticulation (i.e. idiosyncratic spontaneous movements of the hands and arms during speech); language-like gestures (i.e. like gesticulation, but grammatically integrated in the utterance); pantomimes (i.e. gestures without speech used in theater to communicate a story); emblems (e.g. insults and praises); sign language (i.e. a set of gestures and postures for a full fledged linguistic communication system).

Later, McNeill (2000) enriched this continuum and he divided it into four continua by using characteristics as 'relationship to speech', 'relationship to conventions', 'relationship to linguistic properties', and 'character of the semiosis'. McNeill (1992) has identified a number of different types of gestures that speakers routinely use when they talk: iconics (i.e. gestures depicting a concrete object or event and bearing a close formal relationship to the semantic content of speech); metaphorics (i.e. as iconics but depicting an abstract idea); deictics (i.e. gestures pointing to something or somebody either concrete or abstract); beats (i.e. gestures with only two phases (up/down, in/out) indexing the word or phrase it accompanies as being significant). Iconic gestures and abstract deictic gestures are called also representational (McNeill 1992; Kita 2000). McNeill (1992) is concerned with gestures similar to gesticulation as defined in Kendon's continuum (Kendon 1988; McNeill 1992). Gesticulation is the most frequent type of gesture in daily use and it covers many variants and usages. It is made chiefly with the arms and hands but is not restricted to these body parts; the head can take over as a kind of third hand if the anatomical hands are immobilized or otherwise engaged, and the legs and feet too can move in a gesture mode. McNeill (1992) claimed that there was no body 'language', but that instead gestures complement spoken language. Gesticulations would be distinct from 'emblems' because they are obligatory associated with speech while emblems and pantomimes may be delivered in utter silence (see McNeill 1992, 2000; Goldin-Meadow 1999; Kendon 2004).

There are two alternative views about the relationship between gesture and speech. The first posits that gesture and speech are two different communication systems (Levelt *et al.* 1985; Hadar *et al.* 1998; Krauss & Hadar 1999). According to this view, gesture works as an auxiliary support when the verbal expression is temporally disrupted or word retrieval is difficult. The other view (McNeill 1992; Kendon 2004) posits that gesture and speech form a single system of communication, since they are linked to the same thought processes even if they differ in expression modalities. According to the view held by McNeill (1992) and Kendon (2004), we have hypothesized that manual gestures and speech share the same control circuit (Bernardis & Gentilucci 2006; Gentilucci *et al.* 2006; Gentilucci & Corballis 2006). This hypothesis can be supported by evidence that speech itself may be a gestural system rather than an acoustic system, an idea captured by the motor theory of speech perception (Liberman *et al.* 1967) and articulatory phonology (Browman & Goldstein 1995). According to this view speech is regarded, not as a system for producing sounds, but rather one for producing mouth articulatory gestures.

We will review neurophysiological and behavioral data in order to support the point that this circuit controlling gestures and speech evolved from a circuit involved in the control of arm and mouth movements related to ingestion. We will suggest that both these circuits contributed to the evolution of the spoken language moving from a system of communication based on arm gestures (Gentilucci & Corballis 2006). These circuits are also responsible for the relations between spoken language and gesture during conversation. That is, these are specific instantiations of more general relations between the control of arm and mouth actions (Willems & Hagoort 2007).

2. Anatomical and Physiological Consideration

The link between gesture and speech (and in general language) supporting the view that gesture and speech are controlled by a same system can be the result of the activity of systems evolved from two classes of neurons recorded in monkey premotor area F5.

Based on cytoarchitectural and histochemical data, the agranular frontal cortex of macaque monkey has been parceled by Matelli and colleagues (Matelli *et al.* 1985, 1991) in the areas shown in Figure 1a. Area F1 corresponds basically to Brodmann's area 4 (primary motor cortex), and the other areas correspond to sub-divisions of Brodmann's area 6. Areas F2 and F7, which lie in the superior part of area 6, are referred to as 'dorsal premotor cortex', whereas areas F4 and F5, which lie in the inferior area 6, are referred to as 'ventral premotor cortex' (Matelli & Luppino 2000).

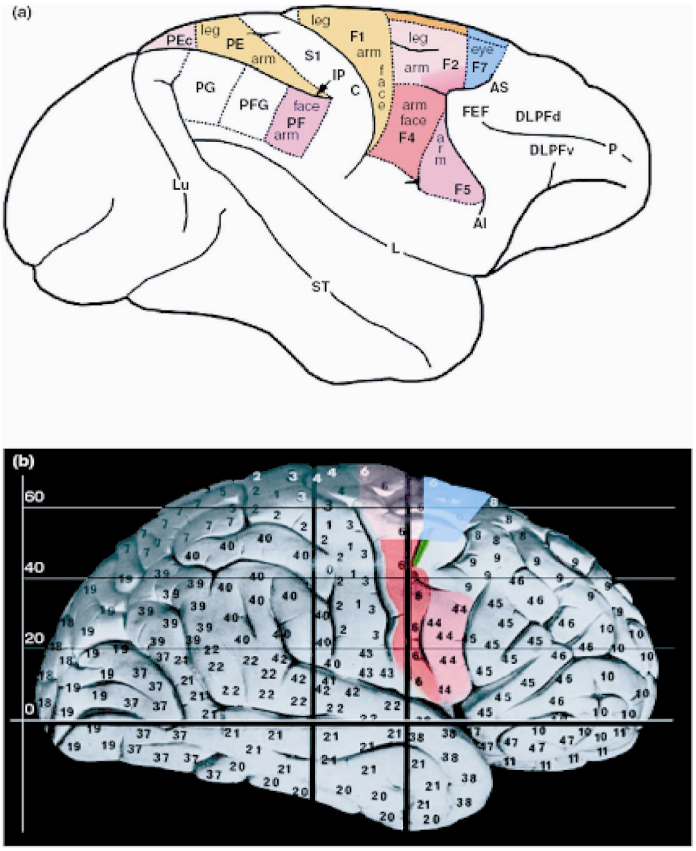

Figure 1: Lateral view of the monkey (a) and human (b) cortex

Neurophysiological studies showed that in area F5, which occupies the most rostral part of ventral premotor cortex, there is a motor representation of distal movements (Rizzolatti *et al*. 1988; Kurata & Tanji 1986; Hepp-Reymond *et al.* 1994). Functional and multi-architectonic data have demonstrated that this area is not a single entity but it consists of three main sectors: F5c, designated as 'convexity', is located on the postarcuate convexity cortex; F5p designated as 'posterior' is located on the posterior bank of the arcuate sulcus dorsally and F5a, designated as 'anterior', on the posterior bank of the same sulcus ventrally (Fig. 2a–b; see Belmalih *et al.* 2009; Gerbella *et al.* 2011).

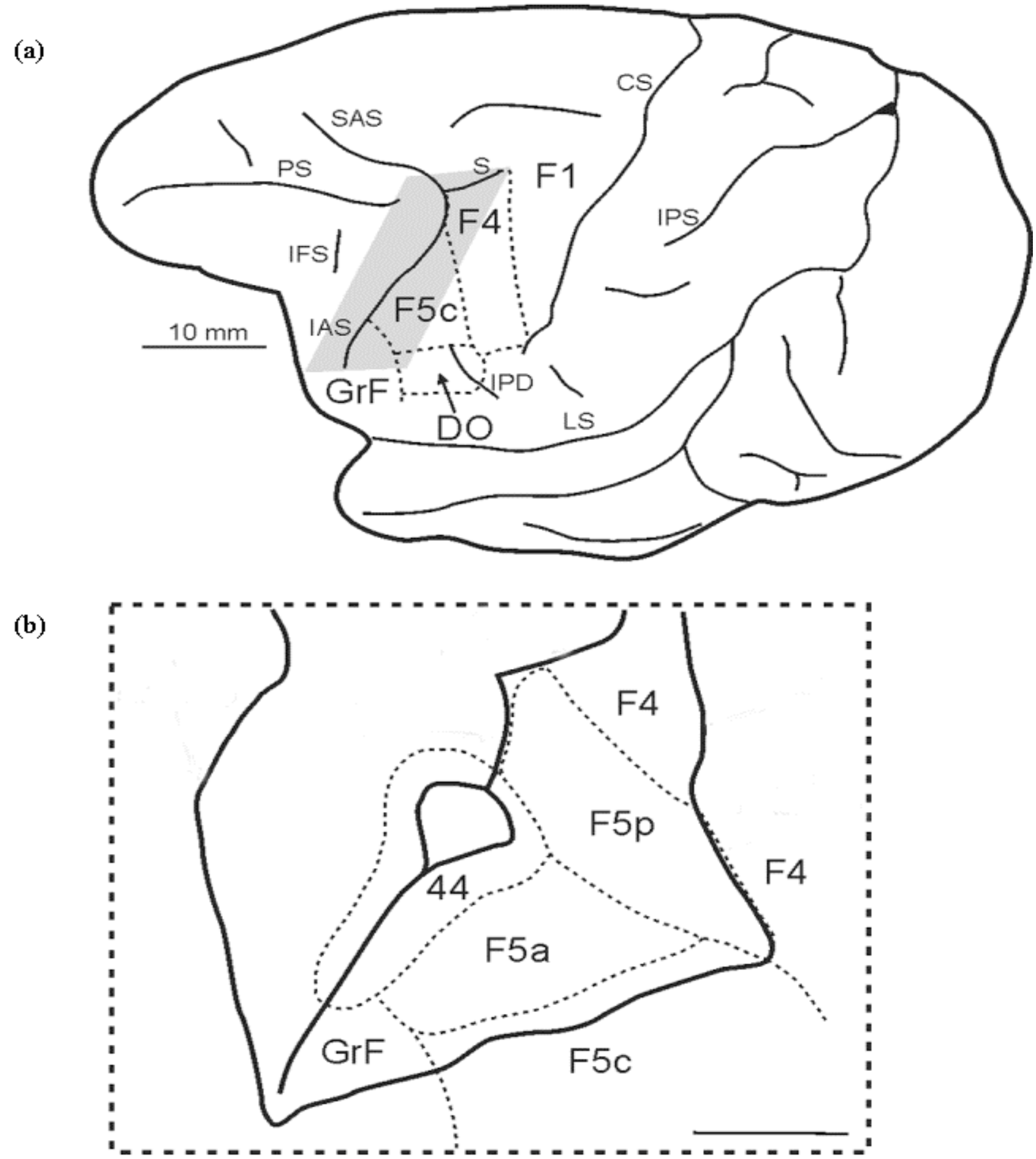

Figure 2: Architectonic maps of the macaque PMv as proposed by Belmalih et al. (2009)

In area F5 two classes of neurons were recorded, which might have been instrumental in the development of a system controlling speech and gestures. The first class of neurons frequently recorded in the posterior part of the inferior postarcuate bank (F5 sector of the arcuate bank in Rizzolatti & Luppino 2001; sector F5c in Gerbella *et al.* 2011) commands grasp actions with hand and mouth (Rizzolatti *et al.* 1988). A typical neuron of this class discharges when the animal grasps a piece of food with its mouth or when the animal grasps the same piece of food with the hand contralateral or ipsilateral to the recorded cortical side. Frequently, the discharge of this class of neurons is selective for a specific type of grasp (for example, a neuron discharges when a precision grasp is used, but not for a power one), and it can be even elicited by the visual presentation of a graspable object, provided that its size is congruent with the type of grasp coded by the neuron ('canonical neurons'; see Murata *et al.* 1997; Rizzolatti *et al.* 1988). Rizzolatti *et al.* proposed that these neurons are involved in coding the aim of the grasp action, i.e. to take possession of an object. From a functional point of view, these neurons can be involved in planning a strategy in order to perform successive grasp actions. For example, they can command the grasp of an object with the hand while preparing the mouth to grasp the same object. From an evolutionary point of view, this circuit of commands might have evolved a system of hand–mouth double command, becoming instrumental in the transfer of a manual gesture communication system, from movements of the hand to movements of the mouth. That is, this system might have been used in language evolution (Gentilucci & Corballis 2006) according to the proposal that language evolved from manual gestures rather than from vocalizations. Indeed, whereas vocalizations of non-speaking primates are mainly related to emotional states, manual actions can provide more obvious iconic links with objects and, consequently, they might have been initially used to represent the physical world (Hewes 1973; Donald 1991; Corballis 1992, 2002; Givòn 1995; Armstrong *et al.* 1995; Rizzolatti & Arbib 1998; Armstrong 1999; Arbib 2005; Ruben 2005; Gentilucci & Corballis 2006). This coupling between hand and mouth, used to transfer a gesture communication system from movements of the hand to movements of the mouth, could also evolve in a system functionally relating gesture and speech.

The second class (the so called 'mirror neurons', MNs) becomes active when the animal executes a transitive action (i.e. acted upon an object) with the hand and when it observes the same action performed by another individual (Gallese *et al.* 1996). In addition, Ferrari *et al.* (2003) recorded discharges in the premotor area F5 of monkeys both from mirror neurons during lip-smacking (the most common communicative facial gesture in monkeys) and from other mirror neurons during mouth movements related to eating. This suggests that non-vocal facial gestures may be indeed transitional between visual gesture and speech.

Finally, mirror neurons in monkey have been also recorded in the rostral part of the inferior parietal lobule (Gallese et al. 2002), and neurons only activated by the observation of movements of different body effectors were recorded in the superior temporal sulcus region (Perrett *et al.* 1989).

According to Rizzolatti and colleagues (Gallese *et al.* 1996; Rizzolatti *et al.* 1996), the mirror neuron activity is involved in representing actions. This motor representation, by matching observation with execution, makes it possible for individuals to understand observed actions. In this way, individuals are able to recognize the meaning and the aim of actions performed by another individual. Therefore, providing a link between an actor and an observer, similar to the one existing between a sender and a receiver of a message, mirror neurons may have played a role in the development of a gestural communication system. Thanks to this mechanism, actions done by other individuals become messages that are understood by an observer. In the present review, we will focus on the system of double motor commands to hand and mouth rather than the mirror system and how it evolved in humans in order to transfer a communication system based on arm actions to mouth postures and it acquired the capability to interact with speech. The role of the mirror system in the construction of a communication system in humans has been reviewed elsewhere (Gentilucci & Corballis 2006; Gentilucci & Dalla Volta 2008; Gentilucci *et al.* 2008).

3. Relations between Execution of Hand/Arm Actions and Speech

A system of double grasp commands to hand and mouth seems to be still active in modern humans, as resulted by the following behavioral studies. Gentilucci *et al.* (2001) showed that, when participants were instructed to open their mouth while grasping objects with their hand, the size of mouth opening increased with the size of the grasped object. The kinematic analysis showed that, concurrently to an increase in kinematic parameters of the finger shaping during the grasp of the large as compared to the small object, there was an increase in the parameters of lip opening even if the participants were required to open their mouth of a fixed amount. Conversely, when the participants opened their fingers while grasping objects with their mouth, the size of the hand opening increased also with the size of the object. Control experiments showed that neither the simple observation of the object nor the proximal component of the reach was responsible for the effect (Gentilucci *et al*. 2001). Recent evidence suggests that even postures of distal effectors affect grasp. Gentilucci & Campione (2011) found that hand postures, in addition to hand actions, influenced the control of mouth grasp. In two experiments, participants reached different objects with their head and grasped them with their mouth, after assuming different hand postures. In one experiment the hand could mimic the holding of a large or small object or it could be relaxed, whereas in the other experiment the hand fingers could be extended or flexed or relaxed (Fig. 3A–B). The latter experiment was a control experiment whose results could be compared with those of experiments 1 and 2 in which the effects of postures of the mouth (open/closed) and toes (extended/flexed) on hand grasp were studied. In both experiments, the kinematics of lip shaping during grasp varied congruently with the posture assumed by the hand, i.e. it was larger or smaller when it could be explicitly (experiment 1) or implicitly (experiment 2) associated with the grasping of large or small objects, respectively.

Figure 3: Experimental set-up, stimuli, procedure and examples of trajectories in Gentilucci & Campione (2011)

In the successive experiment 3 participants were required to open or to close their mouth, or to maintain it relaxed (Fig. 3C). Then, they performed a manual grasp, maintaining that mouth posture. Maximal finger aperture was larger when the mouth was opened as compared to when it was closed. An intermediate aperture was observed in the relaxed mouth condition. The results of these experiments extend the effects of motor interactions with objects to postures of effectors; specifically, the posture of one effector (the mouth or the hand) can be a template for the configuration that will be assumed by the other grasping effector (the hand or the mouth) during shaping. Finally, a control experiment verified whether similar relation also exists between foot and hand. Indeed, previous experiments did not verify whether the reciprocal interactions between postures and actions were specific for hand and mouth or they could be extended to other distal effectors, as, for example, the foot.

Participants executed a manual grasp of an object while their right toes were extended or flexed or relaxed. No significant effect of the foot posture was found on maximal finger aperture. This result disproves a link between hand movements and foot postures: on the contrary, a link was preferentially found between hand and mouth. However, evidence (Baldissera *et al.* 2006) does suggest that the control of hand movements can be associated to the control of foot movements (i.e. during coupled hand and foot oscillations a synchronism between these effectors was observed). To explain this apparent contradiction, we can consider that in modern humans the grasping foot has lost the capacity of activating different interactions with objects of different size and shape. For this reason, despite a clock-movement synchronization, hand and foot do not interact with each other, like hand and mouth, which, on the contrary, are both capable of activating different interactions with objects. Also, from an anatomical point of view (see Buccino *et al.* 2001) premotor area where foot is represented is separated from premotor area where the hand is represented. On the contrary, hand and mouth areas are adjacent and partially overlap.

If this system, coupled with the mirror system, is also used to share a communication gestural repertoire of the hand with the speaking mouth, the execution of transitive actions should affect speech, and specifically the production of phonological units. Gentilucci & colleagues required participants to reach and grasp small and large objects while pronouncing syllables (Gentilucci *et al.* 2001). They found that when grasping the large objects as compared to the small objects, the lip opening and parameters of the vowel vocal spectra increased. Conversely, the pronunciation of a vowel during the entire execution of the grasp affected maximal finger aperture (Gentilucci & Campione 2011). Specifically, the vowel /a/ induced an increase in maximal finger aperture if compared to /i/. The vocalization /ɔ/ induced an intermediate effect. The vowel /a/ is characterized by higher Formant 1 (F1; depending on internal mouth aperture) and lower Formant 2 (F2; depending on tongue protrusion; Leoni & Maturi 2002). In contrast, /i/ is characterized by lower F1 and higher F2. The vowel /ɔ/ has intermediate values. In sum, configurations of the internal mouth related to vocalizations seem to be responsible for effects on finger shaping during grasping. This coupling can be precursor of more complex interactions between gestures and words.

4. Interactions between Gestures and Words

Chieffi *et al.* (2009) studied the relations between production of deictic gestures (HERE, i.e. a pointing directed towards the agent's body, and THERE, i.e. a pointing directed towards a remote point far from the agent's body) and the simultaneous pronunciation of the words QUA 'here' and LÁ 'there'. The authors found facilitation/interference when the meaning of word was congruent/incongruent with the gesture direction; that is, the gesture was quicker in the case of congruence with word meaning. This can be explained by considering that direction was stressed by the word. The reverse occurred in the case of incongruent meaning; that is, the direction was ambiguous because the direction coded by the word was opposite. Consequently, gesture was slowed down. A non-alternative explanation is a priming effect of the word on arm velocity. This suggests an interaction at a higher level due to the presentation of linguistic stimuli.

The relations between gestures and words were also studied when communicative signals like CIAO, NO, STOP were produced (Bernardis & Gentilucci 2006; Gentilucci *et al.* 2006; Barbieri *et al.* 2009). The main finding of these studies was that the social intention, i.e. the intention to interact directly with a conspecific (depending on the communicative meaning of the signal) was transferred from gestures (i.e. emblems) to words, modifying some voice parameters. In turn, following this transfer, the mouth controller modified the hand/arm kinematics by slowing down it. This could be consequent to the fact that the transferred aspects of the social intention coded in the gesture became redundant.

Summing up, in all studies (Bernardis & Gentilucci 2006; Gentilucci *et al.* 2006; Barbieri *et al.* 2009; Chieffi *et al.* 2009) gesture and speech interacted with each other by reciprocally transferring aspects of the signal meaning. Obviously, these aspects differed according to the type of signal.

5. Are the Relations between Hand Postures and Vocalizations Precursors of Relations between Gestures and Speech?

In a previous study, Gentilucci & Campione (2011) found that when subjects pronounced the open vowel /a/, which is characterized by a larger aperture of the internal mouth, the finger shaping of a simultaneous grasp was larger than when they pronounced the closed vowel /i/, which is characterized by a smaller internal mouth aperture. In a subsequent study, Gentilucci *et al.* (2012) reasoned that if the relation between hand actions and vocalizations is precursor of the relation between gesture and speech, same or similar effects of meaningful gestures on both simple vocalizations and words should be found. In this study unimanual/bimanual gestures LARGE and SMALL were contemporaneously presented with a vignette close to the actor in which, in experiment 1, either the vowel 'A' (/a/) or 'I' (/i/) was printed, in experiment 2 the word GRÀNDE 'large' or PÌCCOLO 'small', and in experiment 3 the pseudo-words SCRÀNTA or SBÌCCARA (Fig. 4).

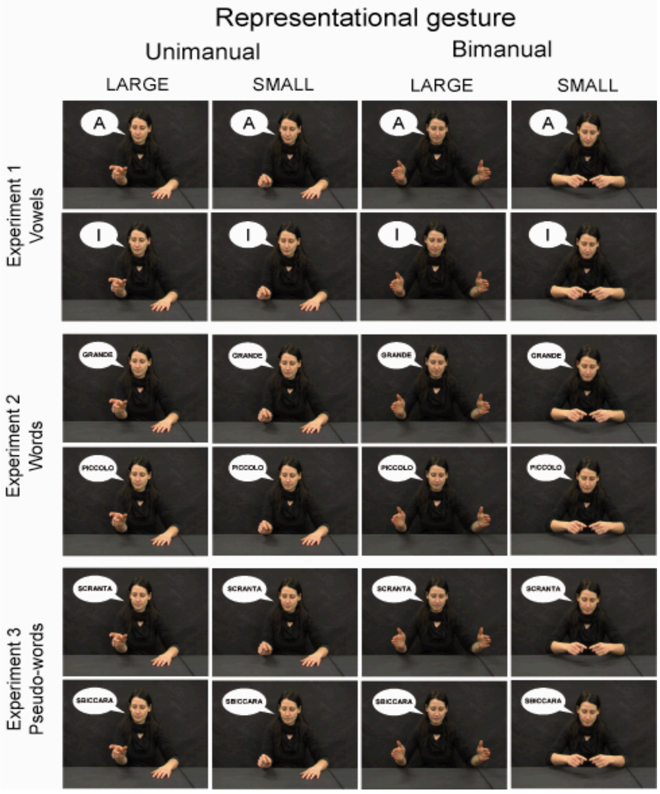

Figure 4: Stimuli presented in experiments 1–3. The panels show all the combinations between gestures and printed vowels ('A' and 'I'; experiment 1) or gestures and printed words (GRANDE, PICCOLO; experiment 2) or gestures and printed pseudo-words (SCRANTA, SBICCARA)

Unimanual gestures affected formant 1 (F1) of voice spectra of the two vowels pronounced alone. This parameter, which is directly related to internal mouth aperture (Leoni & Maturi 2002), increased after gesturing LARGE as compared to SMALL (Fig. 5). F1 of the vowels /a/ and /i/ included in the words GRÀNDE 'large' and PÌCCOLO 'small', respectively, were greater when gesturing LARGE in bimanual condition as compared to the other conditions (Fig. 5). In contrast, F1 of vowels included in the pseudo-words increased when gesturing LARGE in both unimanual and bimanual conditions (Figure 5).

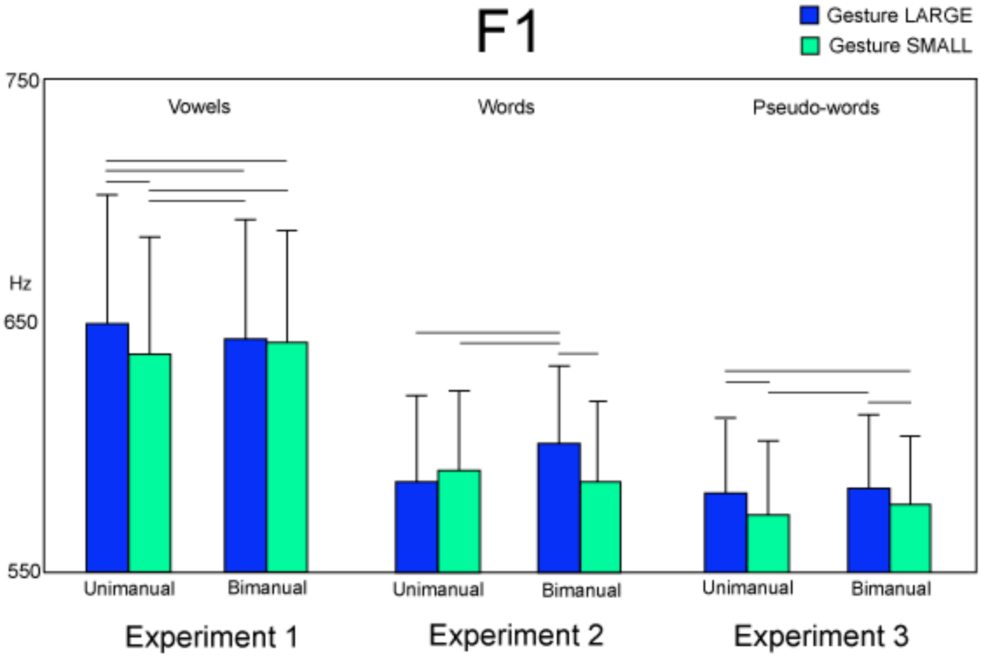

Figure 5: Effects of gestures on Formant 1 (F1) of vowels (experiment 1) or vowels included in words (experiment 2) or vowels included in pseudo-words (experiment 3) pronounced after production of the gestures LARGE and SMALL in unimanual and bimanual conditions. Horizontal bars represent significance or trend to significance in the ANOVAs, whereas vertical bars represent SE.

Summing up, the control of pronunciation of vowels alone was associated to the control of unimanual hand gestures only, according to the hypothesis that the internal mouth and the right hand are controlled by the same system and the two effectors are directly connected (Gentilucci *et al.* 2001; Gentilucci & Campione 2011). Moreover, they support the existence of a more general system reciprocally relating word and gesture meanings. Word meaning was responsible for categorization of all the gestures in LARGE or SMALL. This process was used to construct a size representation common to all the gesturing effectors in which the absolute size was computed. Consequently, the bimanual gesture LARGE was the only categorized as LARGE because the represented size was much greater than the sizes represented by the other gestures: these, conversely, were categorized as SMALLs. In turn, the meaning of the categorized gesture affected word pronunciation. Finally, a size representation not yet independent of the gesturing effectors was activated when pronouncing pseudo-words.

Summing up, we found similarity in the relations between gestures and vocalizations and between gestures and words. However, the differences between the two systems should be discussed. The system gesture/vocalization seems to be simpler since it couples right hand postures with mouth postures. In contrast the system gesture/word seems to be more complex and distributed. This system is involved in a process of abstraction since a size categorization is performed in which the absolute distance rather than that relative to the effector is taken into account.

The gesture LARGE induced an increase in F1 of /i/ of the word PICCOLO and the gesture SMALL induced a decrease in the F1 of /a/ of the word GRANDE; that is, the gesture did not selectively affect the vowels of words whose meaning could be or not associated to the gesture meaning. This result may be explained following the hypothesis that the system relating words and gestures derives from a system relating assumed postures of the hand and simple vowel pronunciation, i.e. due to internal mouth posture. This effect was not selective for vowels (i.e. /a/ vs /i/) and probably this property was conserved in the evolution of the system. This produced predominance of gesture meaning on word meaning in order that the gesture could modulate the meaning of a word. For example the word PICCOLO 'small' could be differently interpreted and pronounced if accompanied by the gesture LARGE or SMALL, respectively. Specifically, the word could be interpreted as less small if accompanied by the gesture LARGE and conversely smaller if accompanied by the gesture SMALL.

Kelly *et al.* (2004) carried out an Event Related Potential (ERP) experiment in which participants saw an actor producing a representational gesture expressing the property like width or height. If the gesture was preceded by a spoken word expressing a different property, a stronger deflexion was observed in ERPs (N400 effect). In many language studies, N400 effect was found when semantic process is harder to integrate into the previous context (for a review, see Kutas & van Petten 1994). Consequently, Kelly *et al.* (2004) interpreted their results as consequent to semantic processing of the gesture. Other studies (Wu & Coulson 2005; Holle & Gunter 2007; Kelly *et al.* 2007; Ozyurek *et al.* 2007) confirmed an N400 effect for incongruence between word and gesture. The data of the study by Gentilucci *et al.* (2012) are in agreement with the idea about a semantic processing of the gesture. Indeed, from a functional point of view the gestures were categorized according to the meaning of the words, and, in turn the meaning of the gestures modulated the meaning of the word.

6. Final Anatomical Considerations

Previously, Gentilucci *et al.* (2006) proposed that Broca's area in Inferior Frontal Gyrus (IFG) plays a role in the reciprocal control between gesture and speech. On the basis of the results by the Gentilucci *et al.*'s study (2012) we extend this proposal; we suggest the existence of two partially overlapping circuits involved in the reciprocal control between gesture and speech. The first is related to the control of vocalization and unimanual gestures (both transitive actions and meaningful intransitive gestures). This circuit can be remnant of the circuit controlling the grasp with the hand and the mouth and it may be located in pars orbitalis of IFG (area BA44, Fig. 1b). This area is involved in encoding phonological representations in terms of mouth articulation gestures (Demonet *et al.* 1992; Zatorre *et al.* 1992; Paulesu *et al.* 1993), in manipulation of complex objects (Binkofski *et al.* 1999), and is part of the human mirror circuit (Gazzola & Keysers 2009; Kilner *et al.* 2009; for a review, see Rizzolatti & Craighero 2004). The second circuit is more involved in the relations between gesture and speech concerning the semantics of the signals. This circuit is enlarged as compared to the first one and may also comprises pars triangularis and/or pars orbicularis of IFG (areas BA45, BA47; Fig. 1b), sectors which are more related to semantics than phonology (Bookheimer 2002). In previous neuro-imaging studies, Willems *et al.* (2007) and Xu *et al.* (2009) found a common circuit comprising pars opercularis, triangularis, and orbitalis of IFG which was activated by the processing of speech or gesture. It might allow a common access of words and gestures to semantics in order to integrate the two signals. In the present study, categorization of unimanual and bimanual gestures on the basis of word meaning might take place in this circuit. In addition, in this circuit transferring aspects of gesture meaning (i.e. the size) to the word might also occur and, consequently, its pronunciation might change. In sum, an enlarged circuit, whose primary (and precursor) nucleus allows a direct communication between vocalization and unimanual gestures (both actions and meaningful gestures), was involved in controlling gestures and words.

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