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Neuronal correlates of grip coding in freely moving monkeys

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Abstract

The investigation of cortical mechanisms underlying the organization of manual actions has so far emphasized the distal components of hand shaping and finger control for grasping as a defining feature of the ventral premotor cortex. An untested assumption of this perspective is that the selectivity of ventral premotor neurons for specific grip types remains consistent when the same object is grasped from different spatial positions - and hence with different body postures - during unconstrained grasping actions.

In this study, we tested this hypothesis by recording single-neuron activity from the ventral premotor cortex of two freely moving rhesus macaques, using chronically implanted floating multielectrode arrays and a 128-channel data logging system. During recordings, the monkeys grasped the same two objects - a large and a small sphere - using a Whole Hand (WH) grip and a Precision Grip (PG), respectively, while the objects were positioned in various locations within the home cage: on the ceiling, on a lower or upper part of the cage wall, or on a shelf. Each object location required different body postures to reach, grasp, and pull: standing and facing upward, sitting and facing forward, or sitting and facing downward with the back slightly bent or straight.

We recorded a total of 288 neurons, of which 54 showed no modulation during grasping actions, while the remaining 234 neurons exhibited significant modulation during grasping in at least one position. The proportion of modulated neurons was consistent across positions, as was the fraction of grip-selective neurons. Some neurons (n=99) showed no grip selectivity in any of the four positions. Among grip-selective neurons, only 4 cells (3%) maintained the same grip selectivity across all tested positions, 9 neurons (7%) exhibited the same selectivity in three positions, 23 neurons (17%) in two positions, and the majority (n=79, 58%) encoded the grip type exclusively in one of the four positions. Notably, a substantial fraction of grip-selective neurons (n=20, 15%) displayed different grip tuning depending on the object's location.

We subsequently conducted a head-free intracortical microstimulation (ICMS) study, observing evoked axio-proximal movements involving the head, forelimb, and face/mouth. We found that stimulation at sites with grip-selective and grasp-related neurons predominantly evoked axio-proximal responses (43% at grip sites and 52.6% at grasp sites), while hand responses were observed less frequently (12.8% at grip sites and 12.3% at grasp sites).

These results suggest a substantial dependence of distal grip selectivity in premotor neuron activity on the axio-proximal postural component that accompanies the execution of grasping actions.

1. Introduction

The premotor cortex (PMC) of non-human primates has been extensively studied for its complex functional organization (Rizzolatti et al., 1988; Taira et al., 1990; Sakata et al., 1995) and its role in representing and planning both distal and proximal limb movements. Distal movements, such as grasping, are believed to be primarily mediated by specific neurons within the rostral part of the ventral premotor cortex (PMv), where cells respond to precise finger configurations (Rizzolatti et al., 1988; Rizzolatti and Luppino, 2001; Schaffelhofer and Agudelo-Toro, 2015; Schaffelhofer and Scherberger, 2016). Inactivation of this area results in impairments in visually guided object grasping (Fogassi et al., 2001). In contrast, control of proximal movements, which involve body joints like the shoulder and elbow and are traditionally associated with reaching, has been primarily attributed to the dorsal premotor cortex (PMd). This has been demonstrated through neurophysiological (Luppino and Rizzolatti, 2000; Wise et al., 1997) and anatomical studies (He et al., 1993; Tanné-Gariépy et al., 2002). However, more recent studies have suggested that the boundaries between these regions may not be as distinct as previously thought. Some of them have identified distal movement-related sites within the PMd (Dum and Strick, 2005; He et al., 1993; Raos et al., 2004) and showed that neural activity in the PMv can be modulated by reach direction (Schwartz et al., 2004).

Woolsey and colleagues (1952) were among the first to highlight that the organization of the upper limb representation in the cortex might follow an anteroposterior arrangement. According to their hypothesis, the fingers would be represented in the posterior part of the precentral gyrus and within the central sulcus, while proximal parts of the limb, such as the arm, shoulder, and trunk, would be characterized by a more anterior representation. However, subsequent studies have demonstrated that the representation of the fingers may not be distinctly separated but rather partially overlapped with that of the wrist, arm, and shoulder (Gould et al., 1986; Donoghue et al., 1992; Park et al., 2001; Rathelot and Strick, 2006). Additionally, the anterior region of the precentral gyrus does not seem to contain a simple representation of the upper arm and shoulder, as Woolsey initially suggested, but rather encompasses a heterogeneous collection of subregions, including one that emphasizes different types of grasping (Rizzolatti and Luppino, 2001).

Alongside this distal representation, studies conducted using intracortical microstimulation (ICMS) have revealed the presence of neurons in the PMv that also encode for the axio-proximal components of the body, such as the trunk, shoulders, and neck (Graziano et al., 2002a; Maranesi et al., 2012). These findings suggest a broader role for the PMv in coordinating complex movements that involve not only the extremities but also the axio-proximal parts, which are essential for body stabilization and spatial orientation during goal-directed movements (Fogassi et al., 1996; Rizzolatti and Luppino, 2001).

However, the majority of studies on grasping in non-human primates have been conducted under restrictive experimental conditions, where the animals were partially immobilized. Under such conditions, postural variations and the resulting changes in the positioning of the axio-proximal parts of the body are severely limited, making it difficult to assess the influence of these variables on neuronal activity within the PMC (Fogassi et al., 1991; Roy et al., 2000, 2002, 2006; Sacrey et al., 2009; Jindrich et al., 2011). Some studies have only gone as far as observing spontaneous grasping movements performed by untrained monkeys, thereby managing to observe the influence of factors such as the final multi-jointed posture of the arm, each of which can, however, explain a very limite fraction of variance of the neuronal discharge (Aflalo and Graziano, 2007). The few studies conducted in freely moving conditions, have been limited to the investigation of kinematic (not the neural) aspects of movement, highlighting the influence of posture on hand preference for performing actions and on the use of various types of grips depending on the different postural conditions (Forsythe et al., 1988; Larson et al., 1989; Masataka, 1989; Sanford et al., 1984; Sartori et al., 2013b, 2014, 2015).

1.1. Functional organization of the premotor cortex

In primates, the frontal lobe is divided into two main regions: the prefrontal cortex, located rostrally and responsible for cognitive functions, and the caudal region, which is involved in movement control. Histologically, the caudal sector is distinguished by its cortex, which is almost devoid of granular cells and is therefore referred to as the agranular frontal cortex (Rizzolatti and Luppino, 2001). For much of the last century, the prevailing view identified two complete representations of body movements in the posterior part of the frontal lobe: one on the lateral cortical convexity and the other on the mesial cortical surface. The first representation, broad and detailed, included the entire area 4 and most of the lateral area 6, known as the primary motor cortex or M1. The second representation, smaller and less precise, emphasized proximal-axial movements and was referred to as the supplementary motor area or SMA (Penfield and Welch, 1951; Woolsey et al.,1952).

Subsequently, this extremely simplified view of the representations of body movements has been replaced by a more complex one, thanks to more refined techniques that have shown how the motor cortex (the agranular sector of the frontal lobe) is composed of a set of anatomically and functionally distinct areas, each of which is involved in the analysis of specific aspects of sensory information. Therefore, there is no single multipurpose area for the perception of space and body schema. Instead, the motor areas are reciprocally connected to the parietal areas (Gharbawie et al., 2011), thus forming a series of specialized circuits that work in parallel, constituting the basic elements of the motor system (Rizzolatti et al., 1998; Matelli and Luppino, 2001).

Based on cytoarchitectural and histochemical data of the motor cortex (Matelli et al., 1985, 1991), the frontal area F1 largely corresponds to Brodmann's area 4 (1909), while the other frontal areas (F2 to F7) are part of Brodmann's area 6. Specifically, F2 and F7, located in the superior part of area 6, are often collectively referred to as the “dorsal premotor cortex”, whereas F4 and F5, situated in the inferior part of area 6, are frequently referred to as the “ventral premotor cortex”. Areas F3 and F6 constitute the mesial area 6 (Rizzolatti et al., 1998), (Fig.1).

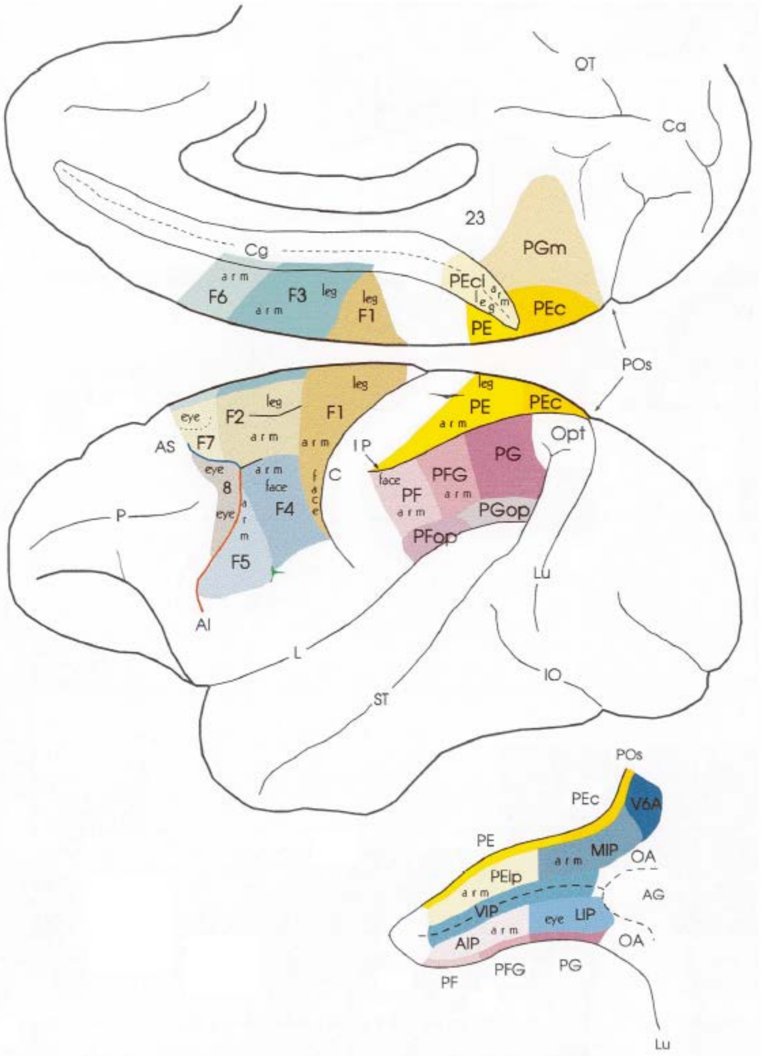

Fig.1. Cytoarchitectonic parcellation of the agranular frontal cortex and the posterior parietal cortex (Rizzolatti et al., 1998). The motor areas have been delineated based on the classifications provided by Matelli et al. (1985, 1991). The terminology adopted here follows the system originally proposed by von Economo for the human cortex, in which all frontal areas, including the motor regions, are labeled with the letter “F”. However, in contrast to von Economo's approach, the individual areas are distinguished by numbers rather than letters. All parietal regions, except those located within the intraparietal sulcus, are defined according to the scheme by Pandya and Seltzer (1982).

1.1.1. Dorsal premotor cortex (PMd)

The dorsal premotor cortex in macaques, specifically Brodmann area 6, includes rostral F7 and caudal F2. While F2 is cytoarchitectonically homogeneous, it is functionally divided into a dorsal part (F2d) and a ventrorostral part (F2vr). F2vr contains bimodal neurons that respond to both tactile and visual stimuli, encoding information crucial for action planning (Fogassi et al., 1999). F2d is associated with proximal arm movements, whereas F2vr is linked to distal arm movements (Raos et al., 2003). F2d primarily receives input from somatosensory-responsive areas PEc and PEip, while F2vr is connected to the medial bank of the intraparietal sulcus (MIP) and area V6A, which integrate somatosensory and visual information for movement control (Colby et al., 1988; Galletti et al., 1996). The rostral part of PMd, F7, receives predominant projections from the dorsolateral prefrontal cortex, implicated in spatial memory (Wilson et al., 1993), and minor parietal afferents from parietal PGm area, involved in object localization (Ferraina et al., 1997). Thus, F7 is part of a cortical circuit involved in encoding the location of objects in space for coordinated arm-body movements.

1.1.2. Ventral premotor cortex (PMv)

The ventral premotor cortex, located in the inferior sector of area 6, comprises two distinct areas: F4 and F5 (Matelli et al., 1985).

Area F4 is involved in encoding movements of the face, neck, and proximal arm (Luppino et al., 1999). Notably, more than half of the neurons in this region possess tactile receptive fields on the body, arm, or face and exhibit bimodal responses by integrating somatosensory and visual inputs (Gentilucci et al., 1988; Graziano et al., 1994; Fogassi et al., 1996). Microstimulation experiments have shown that in F4, movements of the arms, face, and mouth are represented (Gentilucci et al., 1988). Single-neuron recordings have demonstrated that many F4 neurons are activated during reaching movements directed either towards or away from the body, while others are activated during orofacial movements (Godschalk et al., 1981; Gentilucci et al., 1988). Area F4 is the primary target of the ventral intraparietal area (VIP), located in the depths of the intraparietal sulcus (Colby et al., 1993), which receives visual projections from various areas belonging to the “dorsal visual stream” (Maunsell and Van Essen, 1983; Ungerleider and Desimone, 1986; Boussaoud et al., 1990) and somatosensory information from the parietal cortex (Seltzer and Pandya, 1986). VIP neurons are divided into two main categories: purely visual neurons and bimodal, visual-tactile neurons (Colby et al., 1993; Bremmer et al., 1997). The VIP-F4 circuit plays a role in encoding peripersonal space and transforming the positions of objects into appropriate movements towards them (Rizzolatti et al., 1998).

Belmalih et al. (2009) demonstrated that F5 area is not cytoarchitectonically uniform but is composed of three distinct sub-regions: F5 anterior (F5a), F5 posterior (F5p), and F5 convexity (F5c). Two of the sub-regions, F5a and F5p, are located on the posterior bank of the inferior arcuate sulcus, while F5c is situated on the cortical convexity. Among these sub-regions, F5c and F5p exhibit a typical agranular structure, whereas F5a seems to serve as a transitional zone towards the prefrontal cortex (Gerbella et al., 2017). Neuronal recordings in area F5 have identified neurons whose firing is correlated with specific goal-directed motor acts (Rizzolatti et al., 1988). Specifically, using motor acts as the classification criterion, neurons were subdivided into six classes: four related to distal motor acts (“Grasping-with-the-hand-and-the-mouth neurons”, “Grasping-with-the-hand neurons”, “Holding neurons”, and “Tearing neurons”) and two related to proximal motor acts (“Reaching neurons” and “Bringing-to-the-mouth-or-to-the-body neurons”). Most of cells belonged to the distal classes. Additionally, most grasping neurons encoded specific types of hand grasps, such as precision grip, whole hand grasp, and finger prehension (Taira et al., 1990; Sakata et al., 1995).

The anterior intraparietal area (AIP), which occupies the rostral part of the lateral bank of the intraparietal sulcus and contains neurons that are active in correlation with hand and finger movements but not with proximal arm movements, is richly connected with the motor area F5ab (F5 of the arcuate bank; Rizzolatti and Luppino, 2001), where distal arm movements are also represented (Matelli et al., 1994). AIP neurons have been classified into three groups: “motor-dominant neurons”, “visual-and-motor neurons”, and “visual-dominant neurons”. “Motor-dominant neurons” show no significant difference in activity when tested in the dark or light, “visual-and-motor neurons” are less active in the dark than in the light, and “visual-dominant neurons” are vigorously active only in the light (Taira et al., 1990; Sakata et al., 1995). In their 2015 study, Menz et al. focused on how continuous hand and arm movements are represented and encoded in the motor and parietal areas of the macaque brain, comparing the neuronal representation of these movements in the M1, F5, and AIP cortical areas to gain a deeper understanding of how each area contributes to movement planning and execution. They demonstrated that although all three areas contribute to the encoding of continuous hand and arm movements, M1 provides the most precise representation, consistent with its role in direct motor control. In contrast, F5 and AIP offer complementary information primarily related to planning and visuomotor integration. Similarly, Schaffelhofer et al. (2015) explored how different brain regions (motor, premotor, and parietal cortex) in macaques decode complex hand configurations during grasping and object manipulation tasks, focusing on M1, F5, and AIP. The highest decoding performance for planning was observed in F5 and AIP, regions known for their involvement in motor planning and visuomotor transformations. M1, on the other hand, exhibited more intense activity during the execution of movements, as anticipated given its role in controlling motor output.

Additionally, neuroanatomical studies (Luppino et al., 1999; Borra et al., 2008), aimed at identifying and characterizing the anatomical pathways connecting the anterior intraparietal areas (AIP and VIP) to the ventral premotor cortex (F5 and F4), noted a highly selective and reciprocal connection between the neurons of AIP and F5 (Fig.2). Both neuronal populations encode hand movements, particularly in the context of grasping and manipulating objects, and respond to the visual properties of objects (such as size and shape) to determine the optimal way to grasp them. Inactivation of AIP or F5, causing severe deficits in hand pre-shaping during the approach to an object, has also indicated the involvement of these areas in the visual control of grasping and object-directed hand actions (Fogassi et al., 2001; Gallese et al., 1994).

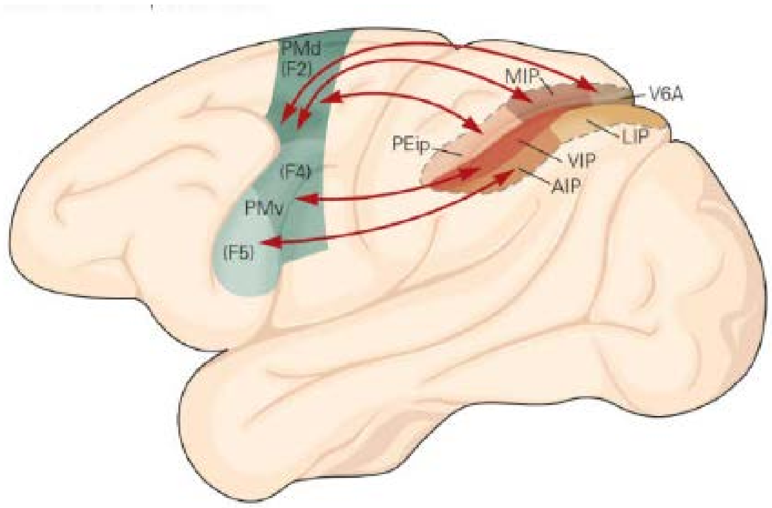

Fig.2. Lateral view of the macaque brain that shows fronto-parietal reciprocal connections supporting voluntary movement. The motor cortex is distinctly highlighted in various shades of green, illustrating its cytoarchitectonic organization. Likewise, the parietal cortex is marked with different shades of red to depict its cytoarchitectonic subdivisions (figure from Kandel et al., 2021).

Thus, the AIP-F5 circuit appears to play a crucial role in transforming the intrinsic properties of objects into appropriate hand movements, with AIP providing an object description in terms of affordances that is then transmitted to F5ab, where different types of grasps are encoded (Jeannerod et al., 1995).

1.2. Somatotopic organization of PMv

The functional properties previously observed suggest that the ventral premotor cortex plays a crucial role in the planning and execution of complex voluntary movements. It is highly interconnected with other motor and somatosensory areas, contributing to fine motor coordination and the modulation of muscle responses.

Early 20th-century studies using electrical stimulation identified motor responses triggered by specific regions of the frontal lobe (Woolsey et al., 1952, 1979), (Fig.3).

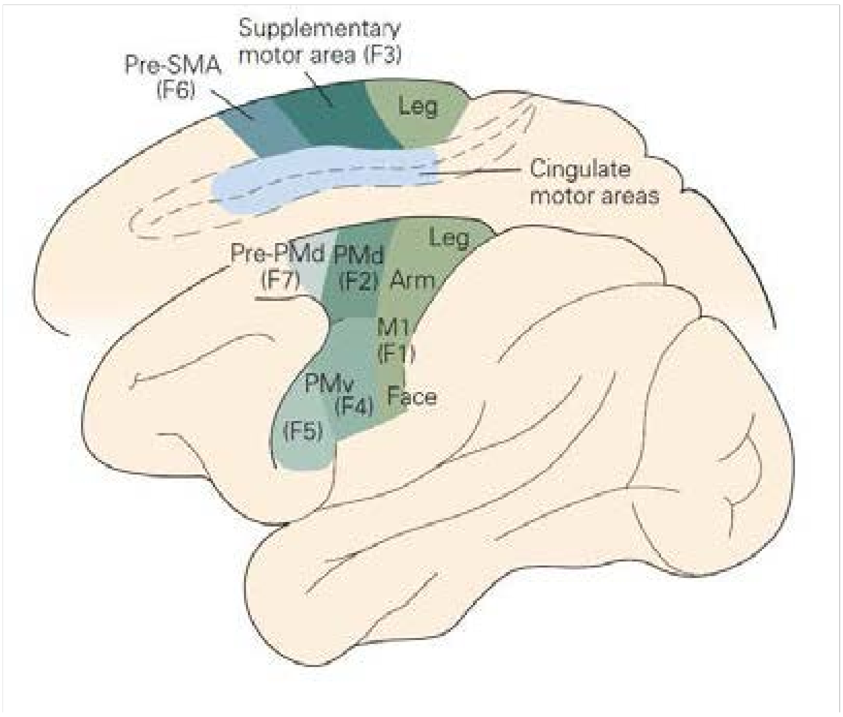

Fig.3. Lateral and mesial view of somatotopic organization of motor areas in monkey brain (figure from Kandel et al., 2021).

Subsequently, the motor maps generated from other experiments revealed a systematic organization along the gyrus, with different regions controlling the face, fingers, hand, arm, leg, and foot. Interestingly, areas of the cortex responsible for finer movements occupy significantly larger portions of the motor cortex compared to regions governing less precise movements (Dum and Strick, 1996). In a study conducted in 1995, Godschalk and colleagues investigated the organization of the premotor cortex (PM) using intracortical microstimulation. They observed that forelimb, hindlimb, and orofacial movements were evoked from extensive regions of the premotor cortex, which appeared to be contiguous with other motor areas. From their results, the PM seems to have a single medial-to-lateral representation of the body oriented parallel to that of M1 and similar to it, except for a greater overlap of the upper limb and face representations in the PM compared to what has been observed in M1 (Sessle and Wiesendanger, 1982; Waters et al., 1990). Comparing the resulting maps with those of M1 and with those of the SMA (Macpherson et al., 1982; Mitz and Wise, 1987), it seems that the upper and lower limbs of the monkey are each represented in an almost continuous manner across the various motor areas of the frontal lobe. The upper limb representation includes not only the M1, the PM, and the SMA, but also passes without interruption from the SMA into parts of area 24 (Luppino et al., 1991; Morecraft and Van Hoesen, 1992). In contrast, the orofacial representation of the PM is located adjacent to and apparently contiguous with the face area of M1. However, the orofacial representation of the SMA does not join the other two orofacial representations, creating an interruption.

From this study, it also appears that the segregation between the lower limb and upper limb representations in the PM is similar to that in M1. However, the extent of overlap between the upper limb and orofacial representations in the PM is clearly greater than in M1. Broad portions of the PMv have either mutual or at least intermixed access to the motor apparatus of both the upper limb and the face, a finding that is in good agreement with the series of studies by Rizzolatti and his colleagues (Rizzolatti et al., 1981; Gentilucci et al., 1983, 1988).

Consistently, in a study conducted by Preuss et al. (1996) on owl monkeys, stimulation of the PMv induced movements of the upper limb, face, and mouth. Although the stimulation produced both distal and proximal movements of the upper limb, distal movements clearly predominated. The authors noted that the minimum currents required to elicit upper limb movements from the PMv were generally higher than those for M1, but lower than those for PMd. When the architectural boundaries of the PMv were identified, it was found that the upper limb representation was located medially within the area. However, within this region, no consistent topographic organization or segregation of distal and proximal movements was observed. Orofacial responses, on the other hand, were sometimes elicited at threshold from the same points that evoked upper limb movements. Orofacial movements unaccompanied by upper limb movements were elicited by stimulating thin bands of PMv cortex caudal and rostral to the core of the upper limb representation, as well as from the cortex lateral to the upper limb representation. Similar to the upper limb representation, no clear topographic organization of different types of oral and facial movements was found across cases.

Subsequently, Graziano et al. (2002a) mapped the primary motor and premotor cortices through electrical microstimulation, building on previous studies that had already used this technique for the same purpose. However, earlier studies employed brief stimulation trains, typically around 50 ms, which evoked brief muscle contractions (Asanuma et al., 1976; Strick and Preston, 1978; Sessle and Wiesendanger, 1982; Weinrich and Wise, 1982; Kurata, 1989; Sato and Tanji, 1989; Huntley and Jones, 1991; Preuss et al., 1996; Wu et al., 2000). Instead, Graziano's research group applied stimulation trains of 500 ms or longer, thereby approximating the average duration of a typical monkey natural action (Georgopoulos et al., 1986; Reina et al., 2001). The results show that with long stimulation trains the evoked movement resemble complex and coordinated multijoint actions similar to specie-specific ethologically relevant actions spontaneously performed by the monkey. The duration of the stimulation train appeared to be the critical factor compared to others (frequency, current amplitude, and pulse type) that were varied alternatively, distinguishing a complete and coordinated movement from a truncated movement or muscle contraction. Many of the evoked movements were highly coordinated across multiple joints. For example, hand-mouth sites involved the fingers closing in a grasping-like movement, the wrist and forearm moving, and the elbow and shoulder rotating to bring the hand to the mouth, accompanied by the mouth opening. In the case of defensive postures, the complex coordination involved one eye closing, the face grimacing, the arm moving laterally, and the hand rotating outward. These movements were mainly contralateral to the stimulated cortex. The results of this stimulation are grossly consistent with the standard somatotopic map in the motor cortex, where the feet are represented dorsally, and the face and mouth are represented ventrally. Specifically, electrical stimulation of certain sites in the precentral gyrus evoked various hand-mouth movements, with different directions of arm movement depending on the initial position of the hand, which was irrelevant with respect to the outcome of the stimulation, always leading to the same final posture regardless of the initial position. Stimulation of other sites in the precentral gyrus also caused the arm to move toward a specific posture and thus the convergence of the hand toward a position in space, or a constant and short-latency movement of the mouth, lips, and tongue toward a specific posture (Fig.4), thereby suggesting the presence of a map of ethologically relevant actions (rather than movements) encoded in terms of final body posture and spanning the primary motor and premotor territories of the frontal cortex.

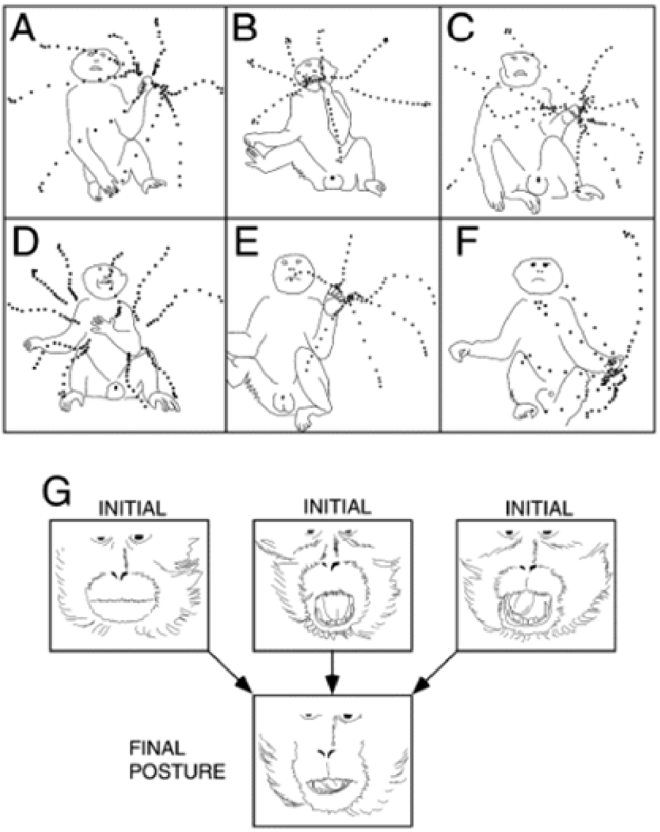

Fig.4. Examples of postures evoked by microstimulation of precentral cortex. (A-F) Six examples of postures of the left arm evoked from monkey. (G) A posture of the mouth and tongue evoked from monkey, (Graziano et al., 2002a).

The same authors later explained that the map of postures resulting from the stimulation seemed to include specialized subregions with different functions (Graziano et al., 2002b; Graziano, 2006), (Fig.5).

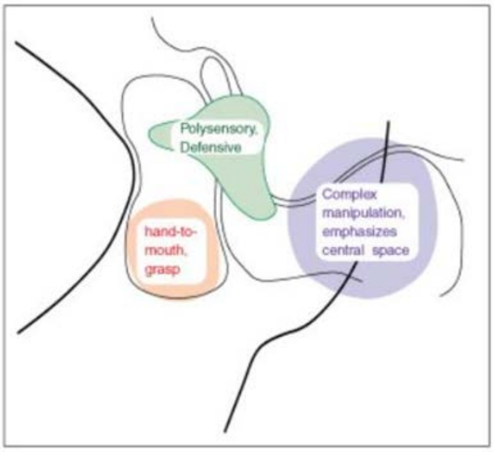

Fig.5. Subregions within the hand position map exhibited specialized characteristics (Graziano et al., 2002b).

One region corresponded approximately to the primary motor area of the hand (green dots in Fig.6), located posteriorly, partially on the gyral surface, and partly on the anterior bank of the central sulcus. This area is responsible for the representation of the hand's position in central space, emphasizing complex manipulation. Another region corresponded approximately to the dorsal and posterior part of area F5 (light blue dots in Fig.6), responsible for representing the hand's position near the mouth, emphasizing finger grasping postures and mouth opening postures. A multimodal subregion located at the centre of the map (red dots in Fig.6), corresponding approximately to the dorsal part of area F4 and the ventro-rostral part of F2, emphasized defensive movements. These results are consistent with those of previous studies, both regarding neurons recorded in F5 involved in arm movements, especially towards the mouth (Rizzolatti et al., 1988), and regarding polysensory neurons with a tactile receptive field on the face, shoulder, arm, or contralateral torso recorded in F4, half of which are also visually responsive (Fogassi et al., 1996; Graziano et al., 1997; Graziano and Gandhi, 2000), which could thus be related to movements consistent with the defence of the body against nearby threatening objects, observed following stimulation of this cortical region, termed polysensory zone (PZ).

For some cortical sites, stimulation evoked an apparent extension in which the wrist straightened, the fingers opened as if to grasp, and the hand reached towards a region of space distant from the body. These sites were typically located only on the gyral surface anterior to the central space/manipulation area and dorsal to PZ (dark blue dots in Fig.6), likely within the dorsal premotor cortex, where a high percentage of neurons respond in relation to reaching movements (Crammond and Kalaska, 1996; Hocherman and Wise, 1991; Johnson et al., 1996; Messier and Kalaska, 2000).

In a wide medial and anterior region (open circles in Fig.6), stimulation evoked particularly complex movements involving both the arm and leg. These were generally bilateral movements resembling climbing or jumping postures. If this functional interpretation is correct, it would be consistent with the fact that this anterior medial area involves the integration of movements from both sides of the body. However, it remains uncertain whether this region lies within the most dorsal part of the premotor cortex, which would explain the involvement of both upper and lower limbs.

Finally, in many sites, stimulation led the hand to a distal position without any clear grip opening, suggesting no apparent specific behavioral purpose. These sites were not clustered in a single area (small black dots in Fig.6) but rather were scattered and surrounded the reaching and central space/manipulation zones.

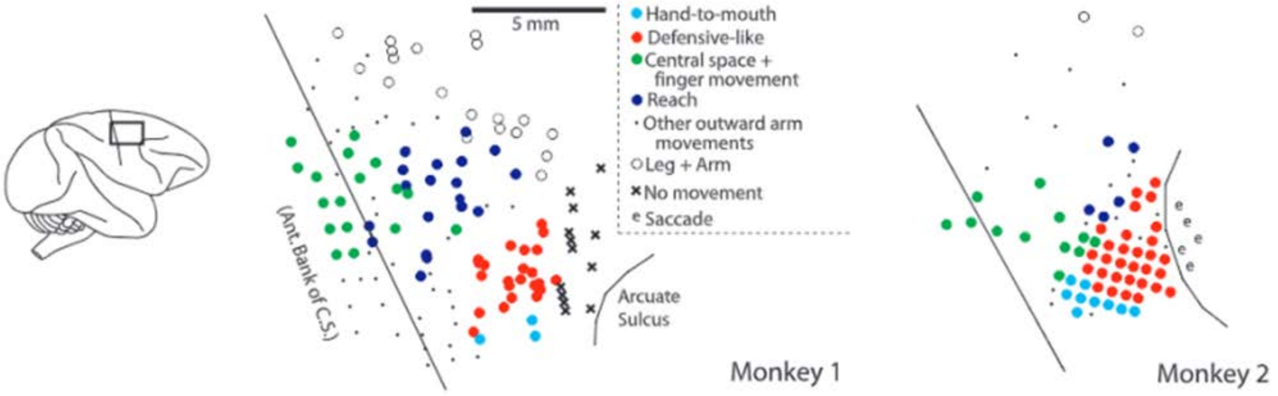

Fig.6. Topographic distribution of stimulation effects. The rectangle on the schematic brain indicates the approximate area of the studied cortex. The diagonal line on the map marks the lip of the central sulcus, with the region to the left of the line representing the unfolded cortex in the anterior bank of the sulcus. The curved line shows the approximate position of the arcuate sulcus. The stimulation sites are color-coded based on the type of complex movement elicited, (Graziano et al., 2005).

1.3. Representation of axio-proximal components in PMv

The fundamental role of the PMv in the planning and execution of voluntary movements, particularly complex ones like grasping, has been corroborated by studies showing that this portion of the cortex not only encodes the final posture of the body but also integrates information about the trajectory and the axio-proximal components, such as the trunk, shoulders, and neck (Maranesi et al., 2012). This integration is crucial for the fine coordination of upper limb movements.

Weinrich and Wise had already demonstrated in 1982 that a substantial portion of movement-related neurons exhibited directional sensitivity, which manifested through three different patterns: neurons with a change in firing only with movement in one direction and no change with movement in the opposite direction; neurons with greater modulation for movements in one direction compared to the other; neurons that became active before movement in one direction and after movement in the opposite direction. In a study by Georgopoulos et al. (1986), single-neuron recordings from the motor and parietal cortices in rhesus monkeys as they freely reached out and touched targets in three-dimensional space, revealed that about 80% of the cells activated during reaching were tuned around a preferred direction. Hocherman and Wise (1991) further confirmed that motor cortical activity associated with movement toward a given target exhibits wide and systematic variability depending on the path taken to reach that target, a property defined here as trajectory selectivity. Therefore, neuronal modulation in the PMv reflects the direction, amplitude, and complexity of movements, integrating sensory and motor information to coordinate precise movements.

ICMS studies, such as those conducted by Graziano et al. (2002a), have highlighted distinct areas within the PMv corresponding to axio-proximal body parts. Stimulation of certain sites caused the elbow and shoulder joints to rotate, bringing the hand gently to the mouth. Initially, it was believed that the shoulder, upper arm, forearm, and fingers were represented sequentially in a dorsoventral map. Woolsey et al. (1952) suggested that the fingers were represented in the posterior part of the gyrus and within the central sulcus, while the upper arm, shoulder, and trunk were represented in a more anterior part of the gyrus. However, whether a true somatotopy exists is currently debated. The anterior region of the precentral gyrus does not appear to contain a simple representation of the upper arm and shoulder as Woolsey thought. Instead, it contains a heterogeneous collection of subregions, including F5 area, involved in encoding different types of grasping actions (Rizzolatti and Luppino 2001).

These results were corroborated by the studies of Gharbawie et al. (2011), which identified distinct pathways between parietal and frontal areas involved in grasping movements, characterized by specific neuronal responses depending on the task performed. Some pathways are more involved in movement planning, while others are crucial for execution. The data suggest that parietal areas provide crucial sensory information to frontal areas, which then orchestrate the grasping movement. According to the authors, the diversity of pathways reflects the complexity of motor control, which requires the integration of multiple sources of information.

In the work by Maranesi et al. (2012), the axio-proximal components are discussed in various contexts related to intracortical microstimulation and their functional organization. The study provides a comparison between the motor responses evoked in the ventral premotor cortex and those evoked in the ventral primary motor cortex. While M1 seems to be primarily involved in the control of fine and precise movements, PMv plays a crucial role in organizing these movements encoding their coordination with axial parts of the body, such as the trunk, to ensure smooth and stable execution of motor actions. The authors also discuss the distribution of functional properties in the F4 and F5 sectors of the premotor cortex, highlighting how these sectors are implicated in the encoding of goal-directed motor acts involving both distal extremities (such as hands and arms) and axio-proximal components. Specifically, ICMS stimulation in different areas of the ventral frontal cortex has evoked movements that include postural adjustments and stabilization movements, which engage the axio-proximal components of the body. This indicates an important role of the PMv in coordinating limb movements with those of the trunk to maintain balance and posture during motor actions.

The influence of axial-proximal components in the coordination of movements raises the possibility of motor synergies that may come into play alongside contextual variables of the action, potentially involving proximal components, which have so far remained unexplored. Supporting the notion of neural coding based on the action's context, Bonini et al., in a 2012 study, investigated how the motor system of macaque monkeys integrates information related to grip type and the context of the action (such as goals like grasping to eat or to place an object), focusing on the inferior parietal region (PFG) and the ventral premotor area (F5). The primary aim of the study was to clarify whether and how information about grip type and the action's goal is processed or integrated at the neuronal level to influence motor behavior. The results indicate that a consistent number of PFG and F5 neurons show selectivity for both the grip and the action goal, demonstrating to be involved in integrating sensory and contextual information to guide goal-directed actions.

Higo et al. (2016) conducted research on the representation of body parts in the motor cortex of macaques. They demonstrated how different cortical areas are involved in encoding body movements. The use of intracortical stimulation provided important information for understanding the functional divisions within the premotor cortices. The authors conducted single-unit recordings in both M1 and PMv during a reach-grasp-retrieval task that involved movements of the mouth and the proximal and distal joints of the forelimb. They studied how neurons in each body representation of the ICMS map responded differentially during the voluntary movement task. The results revealed that neurons located in sites with low stimulation thresholds of the finger representation were more activated during precision grip than power grip and that neurons with low stimulation thresholds in the elbow/shoulder representation exhibited higher normalized neuronal activity during the period just before the grip for both precision and power grip activities. These data together suggest that there is a need for finer control of the fingers in precision grip compared to power grip and that neurons in the elbow/shoulder representation may be involved in the fine control of shoulder movements during grasping.

1.4. Influence of posture on grasping movements in non-human primates

Observational studies have demonstrated that posture differences directly affect movement biomechanics and kinematics, contributing to the motor strategies development in various primate species. Polk (2002) highlights how body mass and limb proportions affect locomotor postures and the musculoskeletal design in cercopithecines. Specifically, animals with longer limbs tend to adopt extended joint postures, reducing joint moments and enhancing the mechanical advantage of extensor muscles. In the context of feeding behaviors, Laird et al. (2022) explored how postural behaviors influence the ability of bearded capuchins (*Sapajus libidinosus*) to manipulate and consume food. The results indicate that the posture adopted during feeding not only supports the movement of the upper limbs but is also essential for coordinating the body and limbs during food manipulation. Finally, Reghem et al. (2013) delve into the influence of body posture on the kinematics of prehension in both humans and gorillas, emphasizing how postural variations can significantly alter trajectories of reaching movement.

Body posture plays a crucial role in determining the effectiveness and precision of movements in non-human primates, influencing not only locomotion but also complex actions such as grasping. Grasping is one of the most important behaviors in primates, and their ability to grasp and/or hold objects with one hand using curved fingers is one of their primary distinguishing characteristics (Napier, 1956, 1961; Bishop, 1962; Costello and Fragaszy, 1988; Christel, 1993; Marzke, 1996; MacFarlane and Graziano, 2009; Reghem et al., 2011; Toussaint et al., 2013; Sustaita et al., 2013). Most kinematic studies in literature that provide detailed information on these types of movements have been conducted by observing animals in unnatural conditions, often in a seated position with some parts of the body constrained during movement (Roy et al., 2000, 2002, 2006; Sacrey et al., 2009; Jindrich et al., 2011). The results of these studies indicate that the shaping of the hand during the action appears to depend primarily on the size of the object to be grasped, which also influences the time required to complete the action (Roy et al., 2000; Sartori et al., 2013a). However, it is important to note that in the wild, non-human primates perform grasping and reaching movements while adopting a variety of different postures, which indeed seem to influence the direction of hand and the choice of the hand with which to perform it (Hopkins, 1993).

In a recent study (2024), Mitchell et al. compared how visually guided reaching and grasping behaviors of non-human primates are studied in laboratory settings versus more naturalistic and ethological contexts, suggesting that adopting more naturalistic approaches could provide a deeper understanding of the neural mechanisms involved. The study discusses the hunting behavior of marmosets, highlighting the complexity of strategies employed depending on the type of prey and environmental conditions. A notable example of natural vision-guided behavior is the capture of flying insects by marmosets. The authors also reference a study that utilized multiple high-speed cameras to investigate the real-time adjustments made by marmosets during reach-to-grasp actions targeting live crickets (Shaw et al., 2023). This approach allowed for an in-depth analysis of the 3D kinematics involved in natural prey capture. The study found that marmosets exhibit short visuomotor delays, akin to those observed in oculomotor systems, when reaching for moving prey. Furthermore, it was observed that visual prediction plays a crucial role in mitigating these delays, enabling the marmosets to adjust their movements on-the-fly.

The only studies in literature that have attempted to observe primates in their natural habitat, in free conditions, have analyzed the influence of various factors on the kinematics of movement. In a comparative study of prehension kinematics between macaques and humans, Christel and Billard (2002) observed subjects performing a task of grasping small food items using a precision grip. The macaques were in non-restrained conditions, thus free to best adapt their body posture. The results showed significantly faster and broader excursions of the elbow and wrist in macaques, who also preferred making a wide excursion of the elbow and a small abduction of the shoulder, in contrast to humans. Sartori et al. (2013b), in a kinematic study analyzing grasping behaviors (power grip and precision grip) while ten adult Old World monkeys (*Macaca fascicularis*) were seated or in a tripod position after moving quadrupedally, found that when seated, the monkeys separately used the two types of grip depending on the object to be grasped, with distinct kinematic characteristics both in the reaching phase and in the grasping phase. The grasping component, however, did not differ in relation to the object when the grasping action occurred in the tripod position. In a kinematic study focused on action selection mechanisms on another sample of adult macaques (Sartori et al., 2014), the monkeys were observed while searching for and grasping objects naturally present in their environment. The results revealed interference effects in movement kinematics when the monkeys grasped a target in the presence of distractors requiring a different type of grasp compared to the target objects, consistent with previous data (Castiello, 1996). Parallel computations for different types of grips, one for the target and one for the distractor, may have caused the variations observed in the movement kinematics directed at grasping a target. In a subsequent study, the same authors (Sartori et al., 2015) observed six young macaques (*Macaca sylvanus*) while they were snatching food from each other or collecting it in the absence of competitors. The study focused on analyzing the spatiotemporal relationship between hand configuration (grasping) and arm movement (reaching) that characterizes grasping actions. The analysis of the results showed that during snatching conditions, the maximum finger aperture was associated with wrist variability, both of which were greater than those found in the condition without competitors.

The results of the studies cited so far suggest that posture influences reach-to-grasp movements in both predictable and variable ways. In controlled experimental conditions, posture shows predictable effects, such as its influence on grasp kinematics and muscle efficiency (Roy et al., 2000; Polk, 2002). There are regularities in joint configuration and hand usage, depending on posture and the object to be grasped. However, in natural or unconstrained settings, posture appears to affect movements in a less predictable manner. Table 1 summarizes the regularities and variabilities identified across different cases.

Study	Observed postures	Posture effects on reach-to-grasp movements	Regularity/variability
Polk, 2002	Locomotor postures	Extended joint postures reduce joint moments, increasing the mechanical advantage of extensor muscles	Regularity in how extended postures improve muscle efficiency
Laird et al., 2022	Feeding postures	Posture supports upper limb movement and is essential for coordinating the body during food manipulation	Regularity in feeding postural behaviors across different substrates (terrestrial or arboreal)
Reghem et al., 2013	Grasping postures	Postural variations significantly influence reaching and grasping trajectories	Variability in posture related to body mass and orientation
Roy et al., 2000, 2002, 2006	Seated, constrained movement	Hand posture during action primarily depends on object size, which influences the timing of the movement	Regularity in grasping actions within controlled environments
Hopkins, 1993	Grasping in natural environments	Posture affects hand direction and the choice of hand used for grasping	Variability based on environmental context
Christel and Billard, 2002	Grasping postures in macaques and humans	Greater elbow and wrist excursion in macaques, with a preference for elbow over shoulder excursion	Regularity in grasping trajectories depending on species
Sartori et al., 2013b	Seated or tripod position	Kinematic differences between grips in a seated position, but not in a tripod stance	Regularity in grasping posture according to body position

Table 1. Summary of kinematic studies on the effects of posture on grasping movements.

In a review by Castiello and Dadda (2019), which aims to consolidate the available literature on the factors influencing the kinematics of reach-to-grasp movements, it is highlighted that body posture has a significant impact on macaques. When executing movements in a seated position, the hand’s kinematics shows adaptations related to the size of the object to be grasped. However, during locomotion, macaques adopt compensatory strategies to maintain balance and coordination. In this same work, which also compares reach-to-grasp movements between macaques and humans, the authors emphasize the existence of similarities between the two species, particularly in controlled conditions, such as the modulation of kinematics based on object size. However, the authors also point out that many experimental conditions have not yet been evaluated in semi-naturalistic and neurophysiological environments. They suggest that such studies could provide a more detailed understanding of the kinematic parametrization in the cortical areas involved in the planning and execution of grasping movements. Despite macaques and humans sharing similar neural structures for controlling grasping movements, it does not necessarily follow that they perceive and motorically interpret objects in the same way, indicating a potential divergence in the use of motor structures beyond physiological characteristics.

In the current literature, there are no neurophysiological studies yet that demonstrate the neural activity of the motor cortices during grasping movements executed in free movement, capable of explaining the influence of postural variables on the distal components of movement. However, in the study by Aflalo and Graziano (2007), the authors attempted to analyze the neural activity of the motor cortex during grasping movements performed by untrained monkeys, meaning with arm movements executed in a spontaneous and unstructured manner. Through this methodology, various models of movement-related neural tuning were observed, revealing that different parameters contribute to the overall neural activity in varying degrees. Specifically, the variables with different percentages of influence on the activity were: hand speed (1%), hand direction in space (8%), a more complex model where the neuron's preferred direction varied based on the initial position of the arm (13%), the final position of the hand in space (22%), and the final multijoint posture of the arm (36%). These results highlight how, when considering a more naturalistic range of movements, motor cortex neurons are partially tuned to multiple parameters rather than just one. The researchers interpreted these results by proposing that each of these factors contributes differently to the total variance of neural activity, with the final posture of the arm representing a particularly significant control parameter.

2. Aims of the study

In neurophysiological literature, grasping has been extensively studied as a fine and highly specialized movement, primarily controlled by portions of the ventral premotor cortex responsible for coordinating distal movements, such as those of the fingers and hand.

Given that most neurophysiological studies to date have focused on animals in restrictive experimental conditions, limiting the understanding of the influence of axial-proximal components on grasping control, this study aims to better understand the neural mechanisms underlying complex motor coordination. Specifically, it seeks to assess the interaction between overall body posture and the modulation of cortical representations of distal movements, particularly within the PMv, under conditions of free movement.

By employing a wireless recording system, we recorded and evaluated neuronal activity related to specific grasping movements during experimental sessions in which two rhesus macaques were required to grasp identical objects that necessitated different types of grip (power grip and precision grip). These objects were positioned at various locations within their home cage, such that the animals had to adopt different postures to reach them. These postures tended to be consistent for each location, allowing for subsequent comparison.

3. Materials and methods

The two subjects of this study (*Macaca mulatta*) had been previously trained to voluntarily sit in a primate chair, enabling the attachment of a head-mounted recording system before each experimental session. Both monkeys underwent surgery to implant a titanium head post (Crist Instruments, Hagerstown, MD, USA) in the context of other experiments, and microelectrode arrays for extracellular recording of single unit activity (Microprobes for Life Science, Gaithersburg, MD, USA). After the surgical procedures, the animals were gradually introduced to the various components of the experimental setup within their home cage environment.

3.1. Ethical statement

All experimental procedures were approved by the Veterinarian Animal Care and Use Committee of the University of Parma and authorized by the Italian Ministry of Health. The research was performed in strict accordance with European legislation on the ethical treatment and use of laboratory animals (Directive 2010/63/EU) and is reported following the ARRIVE guidelines (du Sert et al., 2020). The observations obtained from the first animal were successfully replicated in the second, fulfilling the 3Rs principles required for neurophysiological research. Prior to the study, all researchers and technical staff received a FELASA (Federation of European Laboratory Animal Science Associations) certification for handling nonhuman primates. They were responsible for daily monitoring of the animals' behavior and health throughout the study.

3.2. Experimental subjects

The study involved two male monkeys, W, 13 years old and weighing 12 kg, and R, 11 years old and 13.5 kg.

3.3. Housing and husbandry

The housing conditions for the animals were well above the minimum standards set by Italian and European regulations, with cages (Tecniplast, Italy) offering more than the required 4m³ per animal. Initially, the subjects were housed together in pairs. However, they were subsequently housed separately based on veterinary advice and upon consultation with independent primatologist due to repeated reciprocal aggression episodes and the resulting potential danger for the animals. Nevertheless, animals where always housed in a socially enriched environment, with continuous visual, auditory and olfactory contact with conspecifics.

The living environment was meticulously maintained, with a temperature range of 24-27°C and humidity controlled between 30-40%. The lighting conditions followed a 12-hour light/dark cycle, managed electronically with artificial lighting, and complemented by large windows allowing for natural sunlight each day.

Their diet was primarily composed of various flavored pellets (Mucedola Srl, Italy) and included additional food enrichments such as fruits and vegetables, which were provided by the experimenters after training sessions. Fluid or food were not restricted, but they were administered according to the study protocol and based on individual needs. For bedding, the cages were equipped with sawdust and bark and were cleaned and sanitized daily. The subjects had daily access to an enriched environment, featuring wooden structures and a variety of toys.

3.4. Surgical procedures

To monitor neuronal activity, multi-electrode arrays were surgically implanted into specific cortical regions of both monkeys. Prior to the intracortical electrode implantation, the animals were prepped for anesthesia with atropine (0.03 mg/kg) administered 15 minutes before induction. Anesthesia was induced using a combination of ketamine (4.5 mg/kg) and medetomidine hydrochloride (0.05 mg/kg), and it was maintained with inhaled isoflurane (IsoFlo, 100% p/p). Throughout the procedure, hydration was maintained with a saline infusion at 5 ml/kg/h. To mitigate the risk of seizures following electrode implantation, phenobarbital (2 mg/kg) was given prophylactically, beginning one week before surgery and continuing for four weeks after, with a gradual fade out of the dose over the last two weeks. In addition, antibiotics antinflammatory and analgesics drugs were administered according to the protocol and based on veterinary recommendations.

The implantation of the electrode arrays was guided by MRI-based reconstructions to accurately estimate the margins of the craniotomy. Key anatomical landmarks, including the arcuate sulcus and the central sulcus, were used to pinpoint the insertion site (Fig.7). We utilized chronically implanted floating microelectrode arrays (FMAs), each featuring 32 recording channels (FMA, Microprobes for Life Science, Gaithersburg, MD, USA), for neuronal recordings. Due to their small size and high flexibility, these FMAs allowed for the simultaneous implantation of multiple arrays across different cortical areas. Our custom-designed FMAs included two different electrode lengths (2.5 mm and 4 mm), enabling us to sample various cortical depths (Fig.7A).

Throughout the study, monkey W was equipped with an implant containing 6 FMAs located in the right ventral premotor cortex (Fig.7B), from which all neuronal data were collected. For monkey R, data were initially obtained from 6 FMAs implanted in the left ventral premotor cortex (Fig.7C). However, this implant was later removed and replaced with 6 new FMAs in the right ventral premotor cortex (Fig.7D) for further data collection.

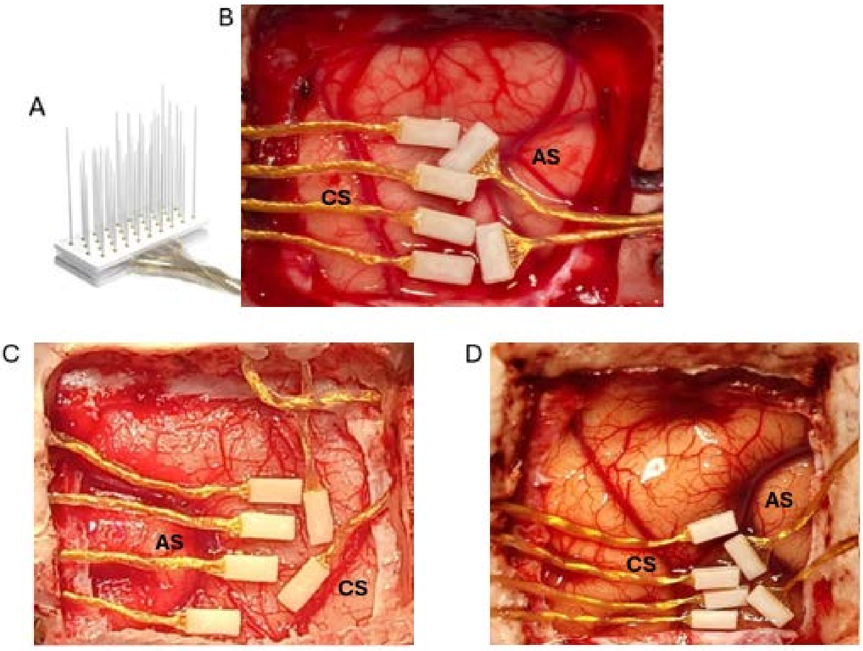

Fig.7. Floating microelectrode arrays (FMAs) implanted in W and R. (A) Schematic representation of a FMA with 36-channels; (B) image of microelectrode arrays placement in monkey W; (C) image of first implant in monkey R; (D) image of second implant in monkey R. Anatomical landmark descriptions: CS - central sulcus; AS - arcuate sulcus.

To secure the implants, customized cranial devices made from PEEK plastic were designed (Fig.8). Two specific head-cap configurations were created: one for normal housing in the homecage (Fig.8A), which had a smaller and slender head-cap, and another for the freely-moving recordings (Fig.8B). The latter configuration featured a larger head-cap to house both the recording system and a small battery, allowing for continuous recording during sessions lasting up to 90 minutes.

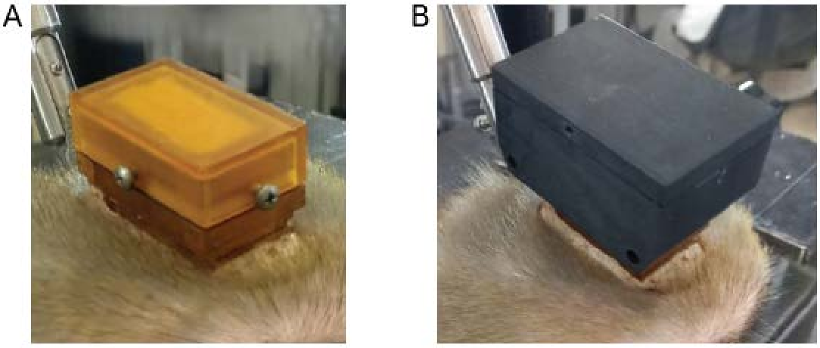

Fig.8. Implant system design. (A) Home-cage configuration; and (B) freely-moving animal configuration.

3.5. Recording techniques

We recorded neuronal activity across 128 channels simultaneously using a wireless data logging system (RatLog-128, Deuteron Technologies, Fig.9A). This system allowed us to apply a band-pass filter ranging from 2 to 7000 Hz with a sampling rate of 32 kHz per channel, enabling the capture of both LFP (local field potential) and single/multi-unit activity signals. The recorded data were amplified, digitized, and stored directly on a 64 GB MicroSD card within the device, eliminating the need for wireless data transmission except for the clock signal, which minimized the risk of transmission errors. The device was powered by a 3.7V external battery connected through a short cable (Fig.9B). After connecting the logger to the electrode arrays via omnetics connectors, the entire setup was secured with a head-cap (Fig.9C).

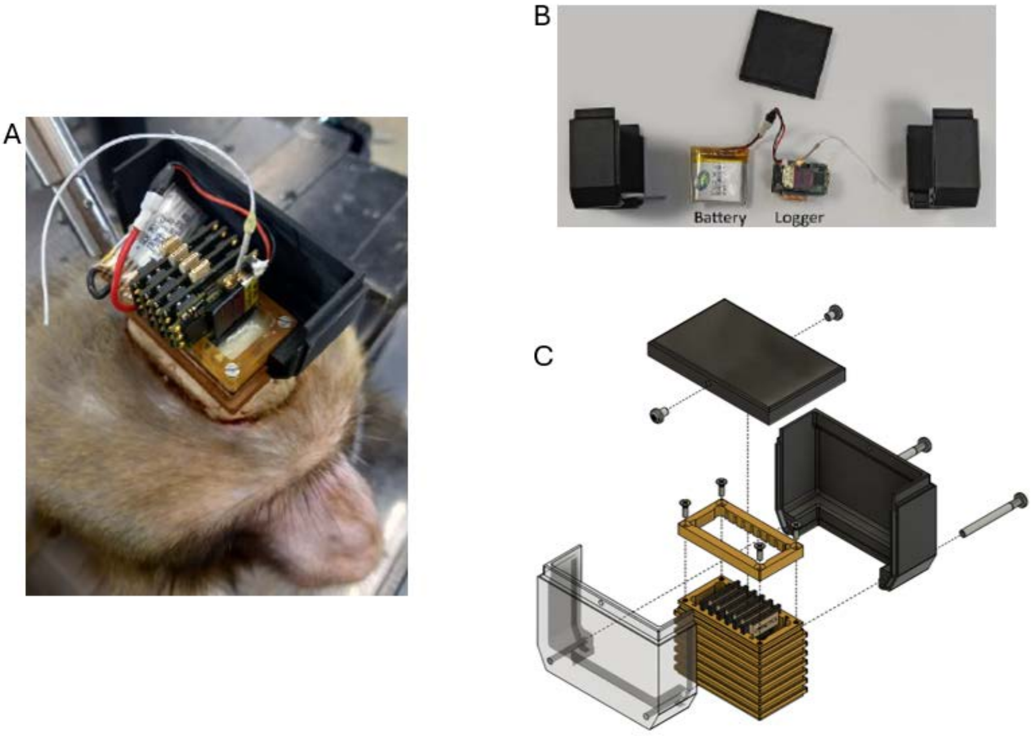

Fig.9. (A) The recording chamber open, divided in its components: (B) the battery connected with the recording system (RatLog-128 from Deuteron technologies); (C) the chamber with the micro-omnetics connectors and the head-cap.

The logger communicates with a computer through a transceiver, following the method outlined by Genzel and Yartsev (2021). The transceiver was also connected to a data acquisition system (DAQ NI USB-6001) via a digital channel.

The video recordings of the sessions were captured using two high-resolution cameras positioned on one side of the animal's home cage, with the interior view enabled by transparent panels. We used color cameras (Basler ace U acA2040-120uc) with a resolution of 2048 px × 1536 px at a maximum frame rate of 120 frames per second, set to 50 Hz. The cameras were equipped with a Global Shutter and a 1/1.8" sensor format with a sensor size of 7.07 mm × 5.3 mm. Each camera was connected via an analog output channel to the data acquisition system (DAQ NI USB-6001).

The setup used and assembled in the enclosure resulted from the integration of the different components (two cameras, the data acquisition system and the neural recording device). The connection of the DAQ system to both the neural recording system and the cameras allowed for synchronization between the neural signal and the video footage. This synchronization was achieved by sending TTL (Transistor-Transistor Logic) signals from the DAQ to both devices simultaneously at the beginning and end of each recording video.

3.6. Training procedures and experimental paradigm

The monkeys were progressively trained to perform a basic grasping task, designed to investigate the neuronal properties during grasping actions on identical objects combined with different spontaneously assumed body postures.

The task was conducted entirely within the home cage of both animals, where four custom-built devices (manufactured by CyNexo Srl, Italy) were fixed for this experiment. Each device consisted of a cylindrical metal base (8 cm in height, 20.7 cm in diameter), on which two spheres (high-density polyethylene, HDPE) of different sizes were mounted at a precise and equal distance on all devices (distance of 11 cm). The larger sphere (4.8 cm in diameter) was designed to afford a Whole Hand (WH) grasp, achieved by wrapping the entire hand around the sphere, while the smaller sphere (1.8 cm in diameter) was designed to impose a Precision Grip (PG), obtained by pinching the thumb and index finger together against the sphere. The spheres were attached to the surface of the metal base through a pin with a spring mechanism, allowing them to be moved forward when grasped and pulled, and to return to their initial position once released (Fig.10).

Fig.10. Device used during the experimental sessions, equipped with a larger spherical object and a smaller one, allowing the animal to perform a Whole Hand grasp and a Precision Grip, respectively.

The four devices were fixed in different orientations so that the grasping actions would be performed in different directions (pulling the object upwards, downwards, or forwards) and in four locations within the cage that required the animal to assume different body postures to reach the objects. Specifically, one device was fixed to the ceiling of the cage in a horizontal position with the objects to be pulled downwards, with the animal standing and reaching toward an overhead position;

another device was placed on a mid-level shelf in a horizontal orientation, with the objects to be pulled upward; a third device was attached to a lower wall of the cage in a vertical position with the objects to be pulled forwards, usually while the monkey was sitting and reaching frontally toward the lower sector; finally, another device was affixed to a higher wall of the cage, also in a vertical position, but at a point that required a different positioning of the forelimbs and back to grasp and pull the objects forwards (Fig.11).

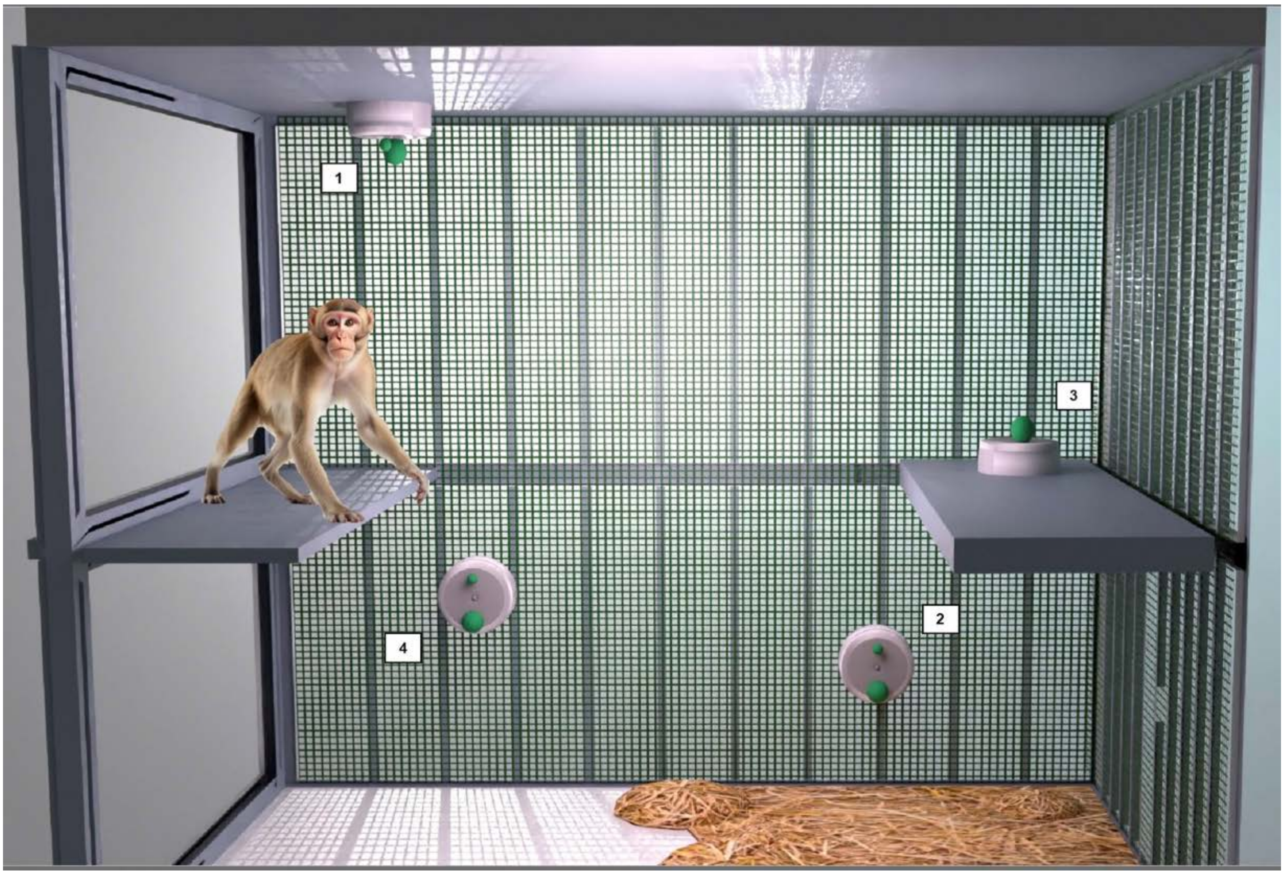

Fig.11. Rendered image of the inside of the animal's home cage, i.e. our experimental setup, which involved arranging the devices inside the animal's home cage as shown in the figure.

By organizing the devices in this manner, the experiment ensured that the monkeys had to use a variety of body postures, depending on the device localization, allowing for a comprehensive analysis of the neuronal activity associated with grasping actions performed under different physical conditions.

The training process involved several stages, starting with familiarizing the animals with the devices. Initially, a clicker sound was paired with the delivery of a positive reinforcement (a liquid reward consisting of fruit juice administered through a syringe) when the animals touched either of the two spheres, regardless of which one. In the next stage, the training progressed by cueing which sphere to grasp using the same syringe that delivered the liquid reward if the monkey grasped the cued object. For each correctly executed trial, a fixed amount of liquid reward (1 ml) was dispensed. This method was maintained throughout the recording sessions.

Each recording session lasted approximately 90 minutes, consisting of two separate 30-minute parts separated by a 30 minutes break. During the first half, the task was performed on the two metal devices positioned at the top of the cage (ceiling and shelf). In the second 30-minute segment after the break, the task was performed on the two devices located in the lower part of the cage (two different heights on the cage wall). During the break, the cameras were repositioned to capture the relevant area of the cage. The target object and the device from which to grasp it were randomized within each pair of simultaneously employed devices. The liquid reward was only dispensed if the object was correctly grasped; otherwise, the cue was removed, and the experiment moved on to the next trial.

3.7. Behavioral analysis

Behavioral analysis was conducted through offline examination of the video-recorded sessions. Using the Behavioral Observation Research Interactive Software (BORIS; Friard and Gamba, 2016), we systematically scored the actions and the postures of both the monkeys. A detailed ethogram (Table 2) was created for this purpose, enabling us to accurately identify and categorize specific behaviors. This approach allowed us to synchronize these behavioral events with the neural data collected during the experiments.

Events	**Definition of the scored event/state**
Reaching onset	The first frame in which the monkey’s right or left arm moves to bring the hand in contact with the small or big object of one device.
Object contact	The first frame after “reaching onset” in which the monkey’s right or left hand makes contact with the small or big object, confirmed by the fact that it is the last before fingers start wrapping around it to secure the grip.
Object pulling	The first frame after “object contact” in which the object detaches from the surface of the device.
Object release	The first frame after “object pulling” in which the object moves back toward the surface of the device.
States	
Standing up	The monkey is standing on its legs with its back straight and whole-body stretched upwards (device 1).
Sitting on the bar	The monkey is seated on a cage bar, typically with the back slightly bent (device 2).
Sitting on the shelf	The monkey is seated on the shelf, typically with its back strongly bent forward and the head flexed (device 3).
Sitting on the floor	The monkey is seated on the floor with its back straight and the head typically facing forward (device 4).

Table 2. Ethogram of the scored behavioral events and behavioral states.

All the behaviors in our ethogram were point events. Independent observers reviewed the experimental session videos to score the behaviors according to the ethogram. Failed grasps and repeated grasps events were excluded from subsequent analyses.

For all trials performed by the animal during the recording sessions, behavioral scoring allowed us to define the various phases of the grasping movements, which were subsequently used in data analysis.

Since the unconstrained paradigm left considerable freedom to the monkeys, the number of correctly performed trials with the contralateral hand differed considerably among devices and objects. Thus, to ensure a comparable statistical power, a qualitative trial selection was performed to ensure that all combinations of grip and device were included for at least X (and no more than Y) correctly performed trials, executed with qualitatively similar postures from the same device.

3.8. Spike sorting and data analysis

All signal analyses were performed offline. Spike detection and sorting were performed with Offline Sorter™ (Plexon Inc), setting a negative threshold of 3 standard deviations from the signal-to-noise on the band-pass filtered signal (4 pole Bessel filter, 300 - 7000 Hz) to detect waveforms, and then applying template matching algorithm to sort the units. For each isolated unit, we verified the consistency of its isolation throughout the task by plotting its spikes in 3D space defined by the first two principal components and the acquisition time. Noisy or physiologically implausible waveforms were excluded from further analyses.

The task was specifically designed to assess possible differences in the neurons firing rates depending on the type of object/grip and the bodily posture adopted to perform it. Data analysis was conducted using MATLAB.

Four epochs were considered relative to the scored behavioral events: 1) a 200 ms epoch prior to the onset of the reaching movement (baseline); 2) a trial specific epoch ranging from first frame in which the animal initiated movement toward the object to object contact (reaching); 3) a trial specific epoch ranging from the object contact to the reference event, i.e., the pulling of the object (grasping); 4) a trial specific epoch from the reference event to the release of the object (releasing). The firing rates were calculated across these four key task epochs: baseline, reaching, grasping and releasing.

Neurons were classified based on possible significant ($p<0.05$) activation during the task epochs across different device positions. To achieve this, we performed four separate 2×4 repeated-measures ANOVAs (factors: Object and Epoch). We set the significance level $p<0.05$. Bonferroni post-hoc test was applied to identify significant differences between epochs and/or their interaction with object type.

Neurons were classified as grasp-related if they showed at least a significant effect of the factor epoch (alone or in interaction), with one or multiple epochs significantly different from baseline (Bonferroni post-hoc test, $p<0.05$); furthermore, they were considered grip-selective if they showed, in addition, a significant effect of the factor Grip, alone or in interaction.

Grasp-related neurons were further classified as either facilitated or suppressed depending on the sign of the modulation relative to baseline of the movement epoch(s) maximally different from baseline in terms of modulation amplitude.

3.9. Intracortical Microstimulation (ICMS)

At the end of the recording sessions, we conducted an intracortical microstimulation study in both monkeys during separate sessions. Monopolar, biphasic trains of cathodic pulses administered via a constant current stimulator (PlexStim, Plexon), with the following parameters: total train length 500 ms or 50 ms, single pulse width 0.2 ms, pulse frequency 200 Hz, and current intensity ranging from 100 to 5 μA. The stimulation was monitored on an oscilloscope and filmed with a camera for further offline analysis of the evoked movement. The recorded/stimulated sites were warped on hemispheres of previously recorded and stimulated animals in which histology was available (Maranesi et al., 2012), and the border between primary motor and premotor cortex was reconstructed leveraging this anatomical comparison combined with the outcome of short train ICMS. Specifically, we considered as putative primary motor cortex those sites where movements could be triggered by short pulse trains at intensities of 25 μA or less, and that were located within 2 mm of the estimated anatomical boundary. The monkeys were placed in a primate chair without their head restrained. ICMS was applied at each site while the monkey was calm and relaxed; instances of voluntary movements were excluded from the analysis of ICMS results. The effectors involved in the movements triggered by ICMS, based on the needs related to our study, were grouped in this way: hand (finger and/or wrist movements), face/mouth (movements of any facial area and jaw or lip movements), and axio-proximal (involving the head, trunk, or the upper portion of the arm between the elbow and shoulder).

4. Results

We recorded single-neuron activity across five recording sessions: three from the right hemisphere of monkey W (n=159), one from the left hemisphere of monkey R (n=66) and one from the right hemisphere of monkey R (n=63), for a total of 288 single units steadily recorded in all conditions. These recordings were obtained from sets of 128 electrodes from all the chronic arrays implanted in the right hemisphere of monkey W and from 128 electrodes chronic arrays (3, 4, 5, and 6) implanted in both the left and right hemispheres of monkey R (Fig.12A).

The typical posture assumed by both experimental subjects to perform the grasping task for each of the different devices is shown in Figure 12B (see also Table 2). By measuring the time taken to complete each phase of the grasping action, it is clear that the different postures associated to each device impact more strongly on the arm reaching component than on the distal, hand-related component of grasping and releasing the object (Fig.12C).

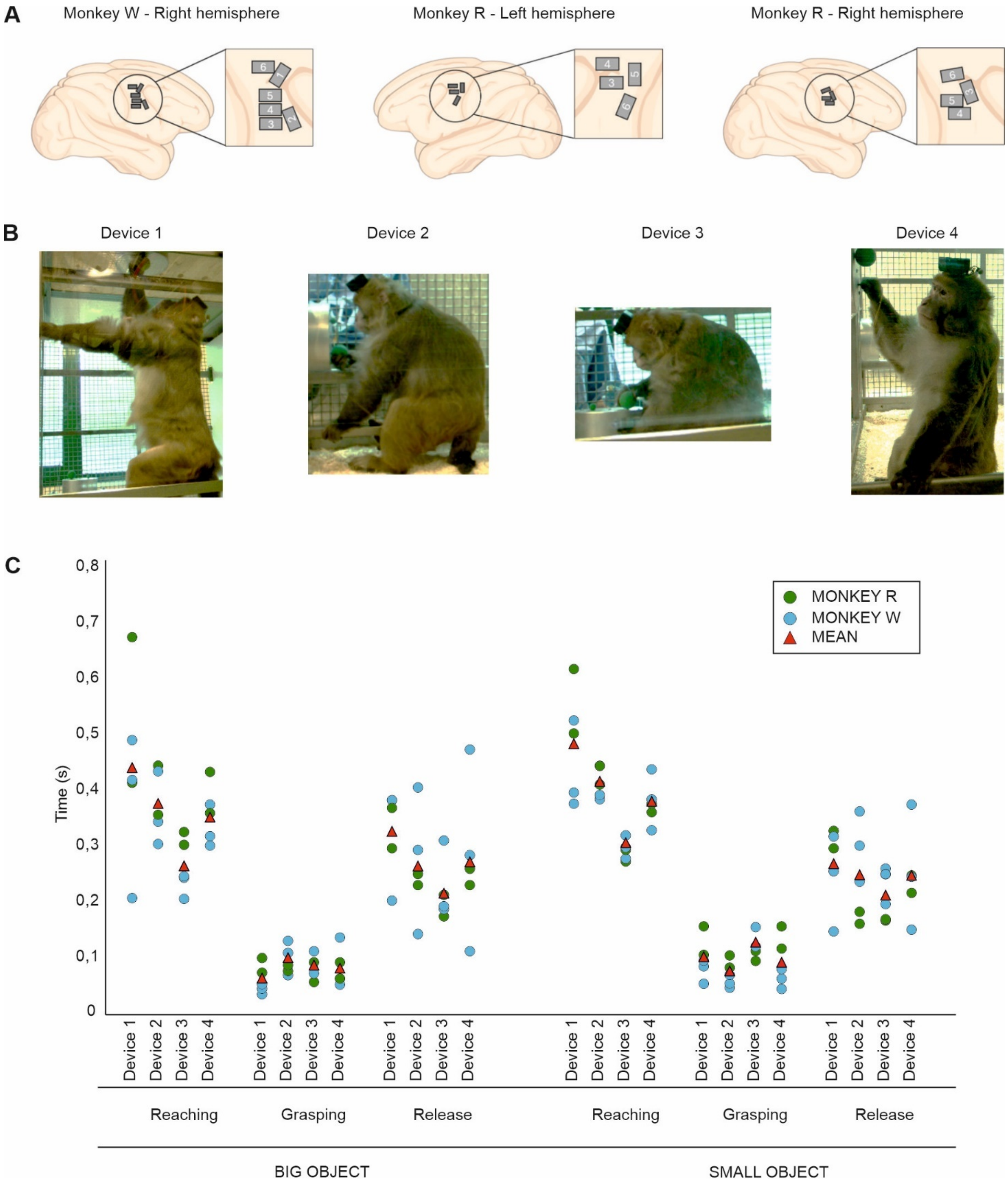

Fig.12. Neuronal recording and behavioral details. (A) Schematic representation of the insertion sites in the premotor cortex of both experimental subjects. (B) Grasping movement performed on each device, with an example of the posture typically adopted by the animal during the trials selected for statistical analysis in each condition. (C) Average duration of each action phase in each of the 5 recording sessions subdivided by animal, grip type and device.

4.1. Single neuron functional properties

To verify if each of the recorded neurons was significantly modulated during grasping execution, we carried out a 2×4 repeated measures ANOVA (factors: Object and Epoch) to compare the putative baseline activity with that during the reaching, grasping, and object holding epochs for each device, separately (Fig.13A). The results indicate that, in each device, about half of the 288 recorded neurons were grasp-related, ranging from 46.9% with Device 3 to 58.7% with Device 1 (Fig.13B). Across devices, the fraction of grasp-related neurons exhibiting selectivity for the type of grip performed by the monkey to grasp the small (Precision Grip) or the big (Whole Hand prehension) object was remarkably similar, ranging from 34.3% with Device 3 to 37% with Device 4 (Fig.13C). Similarly, the percentage of neurons exhibiting facilitated or suppressed discharge was highly comparable across devices, with an overall prevalence of neurons exhibiting facilitated (ranging from 60.5% with Device 2 to 68.6% with Device 1) relative to suppressed discharge (Fig.13D).

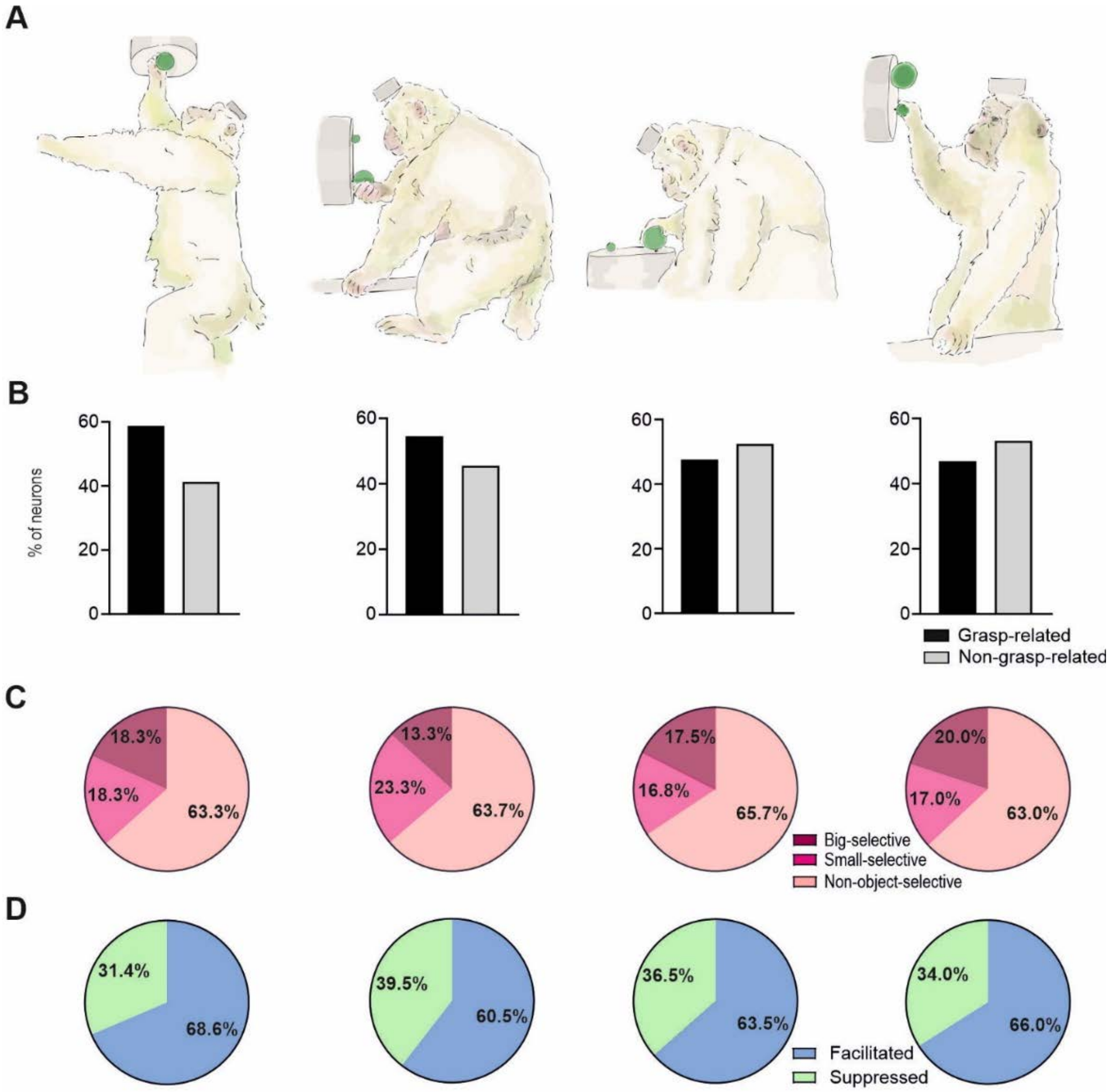

Fig.13. Neurons classification. (A-D) Each section of the panel shows the classification of neurons made following the ANOVA performed separately for each device, as indicated by the image above. The bar graph shows the total number of grasp-related and non-grasp-related neurons. The two pie charts show the classification of grasp-related neurons based on object selectivity (on the right) and modulation type (on the left), respectively.

Based on the considerable similarity in the overall fraction of neurons showing grasp-related modulations across the 4 devices, it could be hypothesized that despite the considerable differences in the body postures, these do not affect the distal encoding of hand movements required to grasp the objects and its neural correlates. Thus, we next investigated the possible similarities or differences in the modulation of single neuron activity during grasping across different devices.

4.2. Neuronal modulation during object grasping across different devices

Based on the results presented so far, the most straightforward hypothesis is that the same neurons exhibit similar modulations and grip tuning across all devices, thereby explaining the observed similarity. To verify this hypothesis, we first counted the cells with a significant grasp-related discharge across multiple devices. Contrary to the initial hypothesis, the results indicate that only 26.5% of grasp-related neurons were significantly modulated across all four devices (e.g., Neuron 1 in Fig.14A), whereas the remaining neurons displayed significant modulations during grasping in only 3 (28.2%, e.g., Neuron 2 in Fig.14A), 2 (21.4%, e.g., Neuron 3 in Fig.14A), or even just 1 (24%, e.g., Neuron 4 in Fig.14A) of the four devices. Thus, although the total number of neurons showing grasping-related activity was quite high (n=234, 81.2%), the majority exhibited variable discharge patterns depending on the location of the device hosting the target objects.

Next, we investigated whether the set of neurons discharging during grasping in all four devices exhibited consistent or differing modulations by applying a 4×3 repeated measures ANOVA (factors: Device and Epoch) across all trials (large object and small object). This analysis aimed to detect any significant main effects or interactions related to the Device factor. The results (Fig.14B) show that, of the 62 grasp-related neurons discharging in all four devices, only 8 did not show any statistically significant main or interaction effect of the Device factor. An example of one of these 8 cells is Neuron 1 in Fig.14A. In contrast, Fig.14C illustrates the most commonly observed pattern: a cell that modulates its firing across all four devices, but with highly variable responses. For example, this cell exhibits complete suppression of firing during reach-grasp movements with Device 4 (located on the ceiling) and a peak increase in firing with Device 1 (located in front of the monkey).

Therefore, almost all recorded neurons displayed variable discharge patterns during grasping depending on the location of the target object in the environment, suggesting that motor components related to body posture influence the activity of grasp-related neurons.

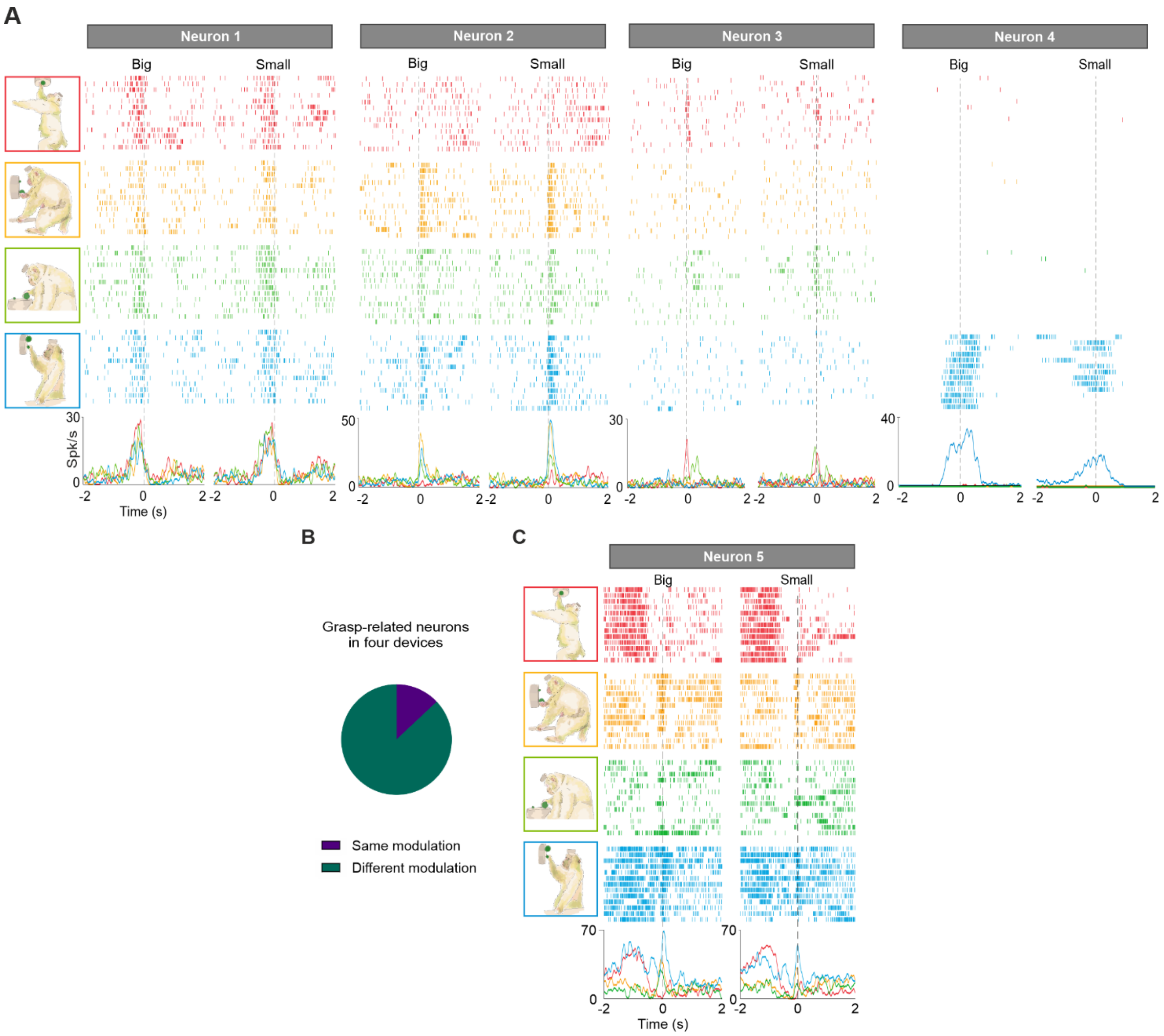

Fig.14. Grasp-related neurons across different devices. (A) Examples of neurons that significantly modulate their discharge in different manner depending on the location of the testing device. From top to bottom: device 4, 3, 2, and 1. Rasters and histograms are aligned on grasping onset (dashed vertical line). (B) Percentage of neurons exhibiting the same or different discharge modulation during grasping of objects located on different devices. (C) Example of a neuron showing grasp-relatedness in all four devices but with highly different modulation profile depending on the device. Conventions as in panel A.

4.3. Grip selectivity across different devices

The highly diverse discharge patterns of grasp-related neurons across devices may suggest that these cells do not encode the distal, hand-related components of grasping, but rather some axio-proximal motor component that modulates during grasping without directly involving hand or finger shape. If this were the case, neurons would not be modulated by the type of grip employed to grasp the object. To investigate this further, we focused on the 135 neurons (57.7%) that discharged differently between the two objects in at least one device (object-selective neurons).

Among these, only 4 neurons (3%) showed object selectivity across all devices; 35 neurons (26%) were object-selective in two devices; 17 neurons (12.6%) in three devices; while the majority (79 neurons, 58.5%) were object-selective in only one device (Fig.15A). These data suggest that even neurons which appear to encode distal features related to hand shape are strongly influenced by the location of the device hosting the objects.

Interestingly, the 4 neurons with object selectivity across all four devices consistently preferred the same object. For example, Neuron 1 in Fig.15B demonstrates a strong preference for the large object, with increased activity during its grasping in all four devices and a marked suppression of discharge when grasping the small object. Among the 17 object-selective neurons in three devices, 9 (53%) consistently preferred the same object, while the remaining neurons shifted their selectivity across objects depending on the device. For instance, Neuron 2 in Fig.15B is selective for the small object in Device 2 and for the large object in Devices 3 and 4. Among the 35 neurons that were object-selective in two devices, 23 (65.7%) consistently preferred the same object, whereas the remainder switched their preference.

In summary, even among neurons with a clear tuning for distal parameters related to grip type, the response and/or grip selectivity were often dependent on the position of the device, suggesting a significant influence of axio-proximal components on neuronal discharge.

To better quantify this effect, we conducted a time-resolved 2×4 repeated measures ANOVA (factors: Object and Device), using the firing rate of each of the 135 object-selective neurons as the dependent variable. This analysis was performed over 200 ms epochs, shifted forward in 20 ms steps within a ±0.7 s time interval from the alignment point (grasp onset). By plotting cumulative results across the neuronal population bin-by-bin, we found that the main effect of the Device factor was markedly more prominent than that of the Object factor or their interaction across the entire action execution period (Fig.15C).

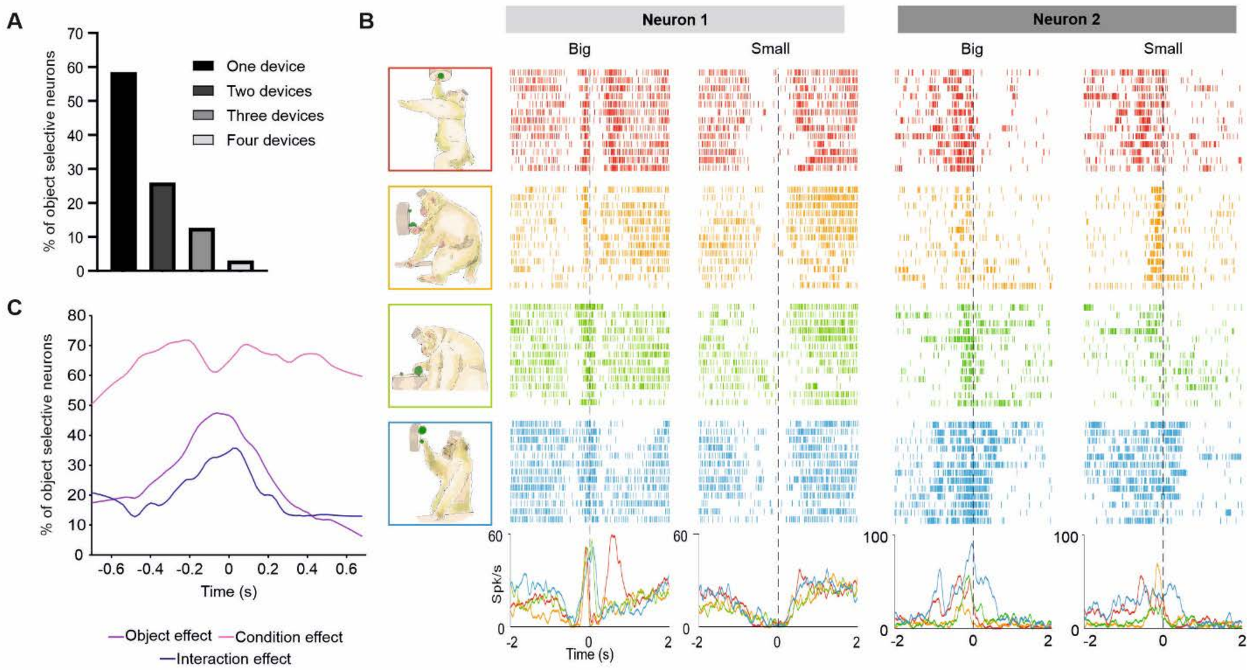

Fig.15. Object-selective neurons across different devices. (A) Percentage distribution of neurons showing object selectivity in one, two, three, or all four devices. (B) Example neurons with object selectivity across different devices. (C) Time resolved fraction of object-selective neurons with tuning for Device, Object, or their interaction. Conventions as in Fig. 12.

4.4. Results of ICMS study

At the end of the recording sessions, we performed an intracortical microstimulation study with long train of pulses (500 ms) and 100 μA of intensity while the monkeys were sitting in the primate chair with their head free. Relative to previous studies (Graziano et al., 2002a, 2005), this approach enabled us to better evaluate the presence of possible axio-proximal component related, for example, to neck/head movement control that would be otherwise impossible to evaluate with conventional head-fixed approach, in which head and trunk movements cannot be distinguished. We primarily focused on cortical sites hosting neurons with grip-selective activity (n=135), neurons exhibiting grasp-related activity without object selectivity (n=99) in at least one device and grasping-unrelated neurons (n=54), and on different types of effects caused by the ICMS (forelimb movements, face/mouth movements, axio-proximal and head movements, not excitable).

In the left hemisphere of Monkey R, we have been able to stimulate only two (specifically, array 3 and array 4) of the four arrays where neuronal activity was recorded. Fig.16A shows the map of the premotor sites from which grip-selective, grasp-related and non-grasp-related neurons were recorded as a function of ICMS evoked motor response (Yates-corrected χ^2= 2.717, p=0.843), and suggests that the different types of neurons are not significantly associated with sites characterized by a specific ICMS outcome.

Fig.16B shows that sites hosting grip-selective and grasp-related neurons, when stimulated predominantly evoked axio-proximal responses (43% in grip sites and 52.6% in grasp sites), more than those that induced a hand response (12.8% in grip sites and 12.3% in grasp sites). Although statistically non-significant, this finding may have functional relevance, suggesting a specialization that warrants further investigation.

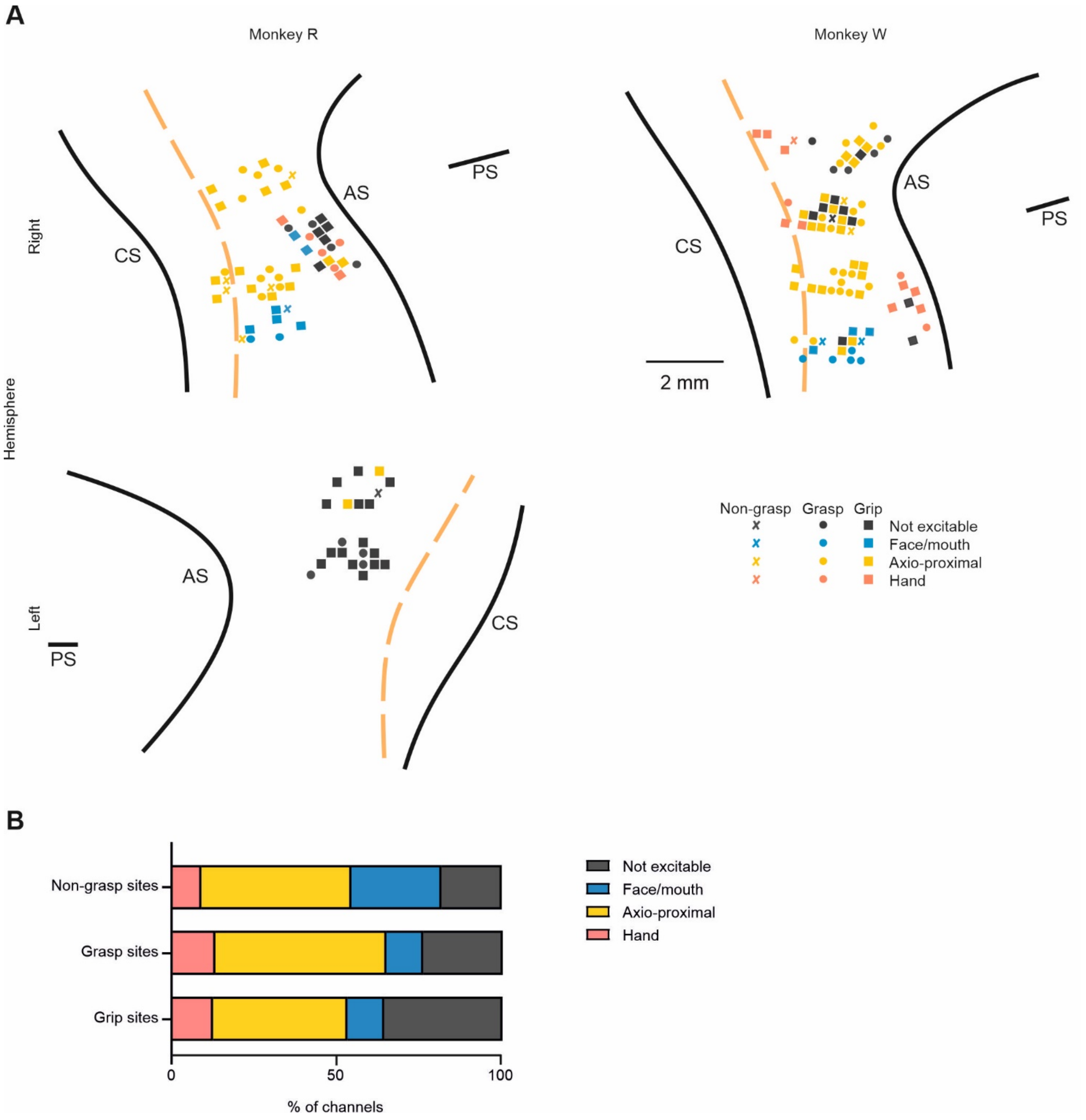

Fig.16. Results of the comparison between motor outputs observed following 100 µA, 500 ms ICMS stimulation and single units recorded during our experimental sessions, in the right hemisphere of Monkey W and both the right and left hemispheres of Monkey R. The orange dashed lines mark the presumed anatomo-functional boundary between the primary motor cortex and the premotor cortex, as determined by prior anatomo-functional evidence (Maranesi et al., 2012). We designated the sites in M1 as those where movements could be elicited by 25 µA pulses and located within 2 mm of the proposed anatomical boundary. CS - central sulcus; AS - arcuate sulcus; PS - principal sulcus.

5. Discussion

In this study, we recorded neural activity from the PMv of two macaque monkeys during a grasping task, using a neuroethological approach to examine neuronal responses in a more naturalistic context than the conventional head-restrained neurophysiological laboratory settings. In these latter studies, animals primarily used distal body parts - such as the hand and the fingers - for reaching and grasping (Taira et al., 1990; Sakata et al., 1995; Schaffelhofer et al., 2015). Restrained setups, however, limit the involvement of axio-proximal muscles, which are essential for postural adjustments during natural movements. Extending free-movement recording techniques, which are common in studies of rodents and other small animals (McNaughton et al., 1994; Buzsáki et al., 2003; Whitlock et al., 2012), to non-human primates can enhance our understanding of brain-behavior relationships from an ecological perspective (Genzel and Yartsev, 2019; Berger et al., 2020; Nourizonoz et al., 2020). Such paradigms allow us to explore questions that conventional methods have not addressed.

In our experiment, we placed two identical objects - a large sphere for Whole Hand grip and a small sphere for Precision Grip - at four different locations in the monkeys' home cages. This arrangement enabled the animals to adopt any preferred posture while grasping, under freely moving conditions. In naturalistic settings, animals grasp objects while maintaining postural stability and adjusting to environmental constraints. Prior research has shown that different food prehension strategies tend to imply specific grip postures (Spinozzi et al., 2004; Pouydebat et al., 2011) and forelimb kinematics (Scott and Kalaska, 1997; Christel and Billard, 2002), as reaching and grasping rely on coordinated movements of the head, shoulder, trunk and, occasionally, the legs, depending on body orientation (Reghem et al., 2013). Our setup allowed grasping actions to be performed in a spontaneous manner, choosing the one that best met postural and environmental demands. Our findings show that the modulation of neuronal discharge in PMv is not uniform across all conditions of the grasping task. Indeed, we observed that activity of individual neurons varies depending on the combination of grip type and location of the object to be grasped in the environment.

Traditionally, the PMv has been associated with hand movement control. By the late 20th century, ICMS studies have demonstrated the role of PMC in distal motor control (Kurata and Tanji, 1986). Later single-neuron recordings revealed that area F5 contains “distal” neurons that respond to hand actions, apparently independently of arm and body positioning, and that are specific to certain grip types (Rizzolatti et al., 1988; Sakata et al., 1995; Raos et al., 2005; Baumann et al., 2009; Fluet et al., 2010; Bonini et al., 2012; Schaffelhofer et al., 2015;). Other studies confirmed that neurons in the premotor area respond selectively during grasping an object with a specific size, shape and orientation (Raos et al., 2004; Fluet et al., 2010), and further suggest that area F5 neurons play a role in integrating information related to object feature for selecting the grip type with contextual information related to the sequence of action in which grasping is embedded (Bonini et al. 2012). Multiunit recordings have shown that grip types can also be decoded with high accuracy from neuronal population (Townsend et al., 2011) and even from local field potential signals (Bansal et al., 2012), suggesting a consistent and widespread representation of information about grip type at a variety of level of resolution. Ad odd with this evidence, however, our results revealed that only a small subset of neurons (n=4) consistently maintained the same grip coding response across all conditions, in contrast with the prediction of a general representation of distal grasping components.

Indeed, most neurons in our dataset exhibited significant variation in response patterns depending on the grasping context. This variability appeared in both the degree of modulation during grasping epochs (i.e., how strongly each neuron was modulated across different conditions) and the type of modulation (facilitation or suppression), which often varied from device to device, suggesting that factors other than the distal type of grip are playing a role in determining the premotor neurons' response. Additionally, we found that a significant portion of neurons (38.5%) displayed object selectivity across only two or three devices, and notably, these neurons often changed their preferred object across conditions.

This variability highlights the importance of considering postural and environmental influences on grasp-related neural activity, aligning with findings from studies on axio-proximal integration in grasping. Woolsey et al. (1952) reported that axial and proximal movements could be elicited by stimulating area 6. Later single-neuron studies showed representations of axio-proximal as well as distal upper limb movements within the premotor cortex (Rizzolatti and Gentilucci, 1988; Rizzolatti et al., 1988). PM neuronal activity during object manipulation involving wrist extension and flexion had also been previously observed (Kubota and Hamada, 1978). Studies comparing PM activity in distal and proximal forelimb movements (Kurata and Tanji, 1986) highlighted the lack of data on these movements under freely moving conditions, where distal movements are accompanied by supporting actions from proximal limb and axial muscles.

In their ICMS studies, Graziano and colleagues (2002a, 2002b) emphasized that PMv stimulation evokes a complex pattern of muscle activity resembling the agonist-antagonist interactions seen in natural movement. They demonstrated that stimulation at certain precentral gyrus sites does not specify a single direction of arm movement but instead produces a final posture involving the arm, hand, and mouth. This muscle activity pattern did not depend on the arm's initial position, indicating that the stimulation determines the muscle coordination required to reach a final posture from any initial state of the body. The integration of postural control during grasping is further supported by other ICMS data showing the representation of axial and proximal body components in the PMv area (Maranesi et al., 2012). However, these studies have a major limitation in unravelling the principle of movement involving axio-proximal muscles, such as those of the head and neck, that could be not visible or significantly altered under head-fixed conditions. Our ICMS study addresses this gap by using head-free animals, allowing us to observe complex, multi-muscle synergies in response to stimulation and to link these responses directly to single-unit recordings on stimulated channels. Notably, we found that grip-selective and grasp-related neurons were associated with axio-proximal motor outputs (40.7% and 51.8%, respectively) rather than with forelimb or hand representation. Thus, the head-free ICMS results reported in this study support a role of combined distal-and-proximal motor synergies as a key representational principle in premotor coding of actions, emphasizing the role of head/neck movement representation causally triggered by head-free microstimulation at the level of cortical sites in which forelimb-related neurons (among others) were found. The present findings are in line with the recent freely moving studies (Lanzarini et al., 2025) and suggest that specific motor synergies that are influenced by the position in space of the object to be grasped are combined with the neural representation of distal hand shape associated with the object features.

Although neurophysiological studies investigating the influence of whole-body posture on grasping movements remain limited, existing biomechanical and kinematic evidence provides valuable insights into the regularities and variabilities associated with these movements. Current literature suggests that posture significantly impacts the biomechanics and kinematics of reach-to-grasp actions, influencing movement direction, muscle recruitment, hand selection, and grasp precision. While controlled environments reveal regular effects of posture on grasping - such as predictable joint configurations and improved muscle efficiency - natural contexts introduce greater variability, with posture modulating movements in less predictable ways. As noted by Polk (2002), for instance, primates with longer limbs tend to adopt more extended joint postures, enhancing the mechanical efficiency of extensor muscles during reaching. This biomechanical regularity suggests that limb length and body mass directly impact the efficiency and direction of grasping movements. Additionally, object properties further influence posture and grasp, as observed by Roy et al. (2000); larger objects generally require a more open hand shape and longer reaching times, indicating predictable postural adjustments that optimize grasp accuracy.

Sartori et al. (2013b) reported that posture affects the type of grip (e.g., precision vs. power) and movement kinematics, with stable postures favoring precision grips over power grips. However, studies in naturalistic settings (Hopkins, 1993; Christel and Billard, 2002) report greater variability in hand use and movement trajectory, likely due to more flexible and less constrained postural demands in dynamic environments. Despite this variability, certain postural consistencies - such as preferred elbow and shoulder configurations - suggest that posture reliably influences motor control strategies across contexts.

The kinematic influence of body posture on grasp execution in freely moving conditions - where postural components support both movement and balance maintenance - may account for the variability observed in PMv neuronal activity during grasping tasks performed in different body positions. This hypothesis aligns with anatomical studies showing direct PMv projections to upper spinal segments, specifically targeting axial and proximal muscles. Wise (2006) described the primate-specific “region C” within PMv, with corticospinal projections confined to upper cervical segments. This organization likely evolved to enable head and upper limb movements, particularly for feeding and visual orientation, facilitating adaptation to an arboreal environment. Complementing this, Borra et al. (2010) demonstrated significant PMv projections from area F5 to the cervical spinal cord in macaques, particularly influencing hand muscles and upper cervical circuits. These findings suggest a functional system whereby PMv influences proximal muscle groups directly through corticospinal projections and indirectly through structures such as the superior colliculus and reticular formations in the midbrain and medulla (Fries, 1985).

As in primates, reach-to-grasp movements in humans represent a key action that enables interaction with and modification of the surrounding environment (Grafton, 2010). Neuroimaging studies on these movements in humans have revealed similarities with primates (Grefkes and Fink, 2005), such as the recruitment of distinct brain areas for reaching and grasping. Specifically, in humans, the dorsomedial circuit, including the PMd, is predominantly involved in reaching movements, whereas the dorsolateral circuit, including AIP and PMv, plays a major role in visuomotor transformation and grip formation (Begliomini et al., 2014). Some studies emphasize the importance of cortico-cortical connections, especially those between the premotor cortex and the primary motor cortex, in facilitating complex actions. The work by Cattaneo et al. (2005) identifies a cortico-cortical mechanism that enhances the excitability of corticospinal neurons in M1 during action preparation. This suggests that preparation for grasping is not solely localized in M1 but also involves the premotor cortex, confirming the findings of Simone et al. (2021) regarding the interaction between different cortical sectors to integrate both the cognitive and motor components of movement. Fornia et al. (2018) also reinforces this view by showing that ventrolateral premotor cortex (corresponding to area F5 in macaques, crucial for grasping) exerts an indirect modulation on M1, representing a necessary connection for action organization. From an evolutionary perspective, the many similarities in the parieto-frontal circuits, which have increased in specialization and efficacy for grasping movements, suggest that primordial parietal networks underlying spatial attention and motor cognition have been preserved through evolution (Caminiti et al., 2015).

In non-human primates, EMG studies have shown that during grasp tasks with varied movement directions and object configurations, proximal muscle activity (shoulder and elbow) is primarily modulated by reach direction, whereas distal muscle activity also reflects grip type (Stark et al., 2007). This finding is useful for understanding how proximal muscles can be selectively activated based on contextual requirements. In humans, scientific evidence also supports the idea that proximal muscles contribute to stabilizing and modulating reaching movements (Chieffi and Gentilucci, 1993). Grinyagin et al. (2005) found that axio-proximal muscles not only stabilize the arm during grasping but also work in synergy with distal muscles to ensure coordinated movement.

These findings on the similarities in cerebral circuits and muscle dynamics involved in reach-to-grasp movements between human and non-human primates have important implications for rehabilitation and the development of neuroprosthetics. The primary goal of neuroprosthetics is to emulate the natural functions of the human motor system. Designing advanced prosthetic devices relies on understanding the observed muscle synergies and neural activations in primates, facilitating more natural and fluid prosthesis control. For example, the STIMGRASP study introduced a functional electrical stimulation device designed to restore grasping in daily activities. This system is particularly useful for individuals with tetraplegia or hemiplegia, as it enables hand opening and lateral grasp movements, improving patients' independence and quality of life (Barelli et al., 2023). In another study on neuroprosthetic use for grasping, prosthetics controlled via electrocorticographic (ECoG) signals demonstrated a 94.5% accuracy in reproducing gripping functions (Márquez-Chin et al., 2009).

Current literature on the involvement of proximal muscles in grasping movements focuses mainly on muscles closely related to the arm. However, observing animals in free movement for the first time enables consideration of axio-proximal movements associated with overall body posture, including trunk and head muscles. This holistic view may lead to a deeper understanding of motor dynamics and more effective therapeutic approaches.

In conclusion, this study, while not yet providing evidence of a direct correlation between body posture and neuronal response patterns, has brought to light several aspects that point us in this direction. Our findings offer reasonable grounds for further exploring this relationship. In particular, the observed variability in neuronal activity across different grasping conditions, despite identical objects being used, suggests that postural changes likely play a significant role in shaping these responses. Future research should aim to investigate this interaction more deeply.

A crucial next step, both fascinating and necessary, is to conduct a detailed 2D and 3D kinematic analysis of the animals during grasping movements, using tracking software (Nath et al., 2019; Karashchuk et al., 2021). This analysis could be applied to both the already recorded sessions in our dataset and new experimental sessions. Such an approach would provide more precise information regarding the positioning of specific body parts (e.g., head, arm, back) and the overall posture adopted by the animal. By doing so, we would gain deeper insights into how posture influences neuronal activity, further advancing our understanding of motor control.

This kinematic analysis could align with the latest neuroscientific trends in examining neuronal responses to specific events, moving beyond the conventional view of movements as isolated and self-contained actions (Berger et al., 2020; Händel and Schölvinck, 2019). Instead, it would consider them as embedded within more complex and comprehensive motor programs that involve the entire body. As a result, this perspective highlights the possibility of significant changes in response patterns that could arise from numerous circumstantial factors, a notion particularly relevant when moving away from restrained animal conditions. By expanding the scope of motor analysis, future studies could provide a more holistic understanding of the motor cortex's role in controlling coordinated, whole-body movements.

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