Brain Area V6A: a Cognitive Model for an Embodied Artificial Intelligence

Fattori Patrizia[1], Breveglieri Rossella[1], Marzocchi Nicoletta[1], Maniadakis Michail[2] and Galletti Claudio[1].

[1]Dipartimento di Fisiologia Umana e Generale, Università di Bologna, I-40126 Bologna, Italy.

[2] Institute of Computer Science, Foundation for Research & Technology - Hellas (FORTH), Science and Technology Park of Crete, Vassilika Vouton, P.O. Box 1385, GR 711 10 Heraklion, Crete, Greece.

Correspondence and proofs should be sent to **Prof. P. Fattori**, at the above address.
Telephone number: +39 051 2091749   Fax: +39 051 251731
E-mail: patrizia.fattori@unibo.it

Abstract. We found that single neurons in the parietal area V6A of the macaque brain deal with all the components of reaching and grasping actions: locating in space the object target of action, directing the eyes toward it, sensing where the arm is in space, directing the arm toward the spatial location where the object is in order to reach and grasp it, adapting the grip to the object shape and size. The knowledge of how the brain codes simple visuomotor acts can be useful to build artificially-intelligent systems that have to interact with objects, localize them, direct their arm toward them, and grasp them with their gripper. Single cell recordings can also be useful in understanding how to perform more complex visuomotor tasks, like interacting with human beings, exchanging objects with them, and acting in an ever changing environment.

An humanoid robot gazes at a dish that it should insert into a dishwasher. The robot reaches the dish with its arm and grasps it with its gripper, lifts the dish, and puts it into the appropriate place on the dishwasher plate.

The robot has produced a sequence of actions that every human being performs naturally and dexterously hundreds of times each day: locating a visual object in space, directing the eyes toward it, directing our arm toward the spatial location where the object is in order to reach and grasp it, adapting the grip to the object shape and size. In order to perform this task successfully, our brain, and also the cognitive architecture of a robot, should know where the eyes are directed, where is its hand in space, and where is located the goal of action is in peripersonal space.

The prehension task is achieved by primates through a series of neural elaborations that are performed in the parietal and frontal lobes. Recording of spike trains from single neural cells and analysis of their modulations according to the different phases of the prehension task are the most used techniques through which we acquire knowledge of how the prehension task is achieved. This is the job of neurophysiologists (like us) who select a brain area (supposed to be involved in certain functions), and record the bioelectrical signals from single cells of that area with fine wire microelectrodes. The frequency of discharge of action potentials (spikes) changes according to the signal that is processed by the neuron itself. The knowledge on how the brain codes the different phases of prehension task can be useful to build up artificially-intelligent systems, in particular to build embodied aspects of cognition. So we propose here a summary of our studies in order to solve some problems that scientists who are involved in artificial intelligence (AI) could encounter.

Neurophysiology of Prehension
We cannot record from the human brain (or can only occasionally, and for a very short time, during a neurosurgery), because of ethical reasons. If we want to know how the human brain works, we have to study the brain of an animal that is able to perform the same task we want to investigate in human. For studying the brain control of prehension, the most used animal is the macaque because its visuomotor functions are almost identical to the human being.

We have been studying for several years a region of the macaque brain known to be involved in visuomotor functions. In particular, we are currently studying the functional properties of neurons of a parietal area called V6A (V stands for visual, as

it was originally identified for its visual properties [1]) which contains visual [2] as well as reaching [3,4] neurons. The visuomotor properties of this area have been intensively studied by our laboratory in the last decade [see 5 for a comprehensive review on this topic]. The following represents a summary of these studies.

The Parietal Area V6A

Area V6A is a brain cortical area located at the boundary between the occipital lobe, classically known to be devoted to the analysis of visual information, and the parietal lobe (Fig. 1). The anterior part of parietal lobe hosts the primary somatosensory cortex, which is the first cortical sector analysing sensory information from the body. The posterior parietal cortex contains several bimodal visual-somatosensory areas involved in the guidance of arm movements.
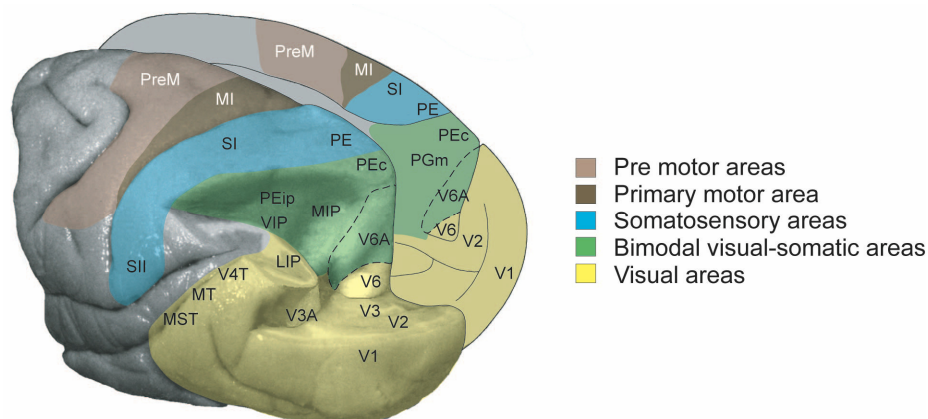

Fig. 1. Cortical areas of the macaque brain.
Left: postero-lateral view of a partially dissected left hemisphere with a part of the inferior parietal lobule and of the occipital lobe cut away in order to show area V6A hidden in the parieto-occipital sulcus. *Right*: medial view of the right hemisphere.
Labels on different brain regions indicate cortical areas according to anatomical and functional criteria. Colors indicate sensory or motor properties of different regions of the brain. Note that area V6A is at the posterior end of the bimodal (visual/somatosensory) region, and borders the visual areas of the occipital pole.

The role of V6A as a visuo-motor area was confirmed after neuro-anatomical studies performed in the macaque brain. This technique is based on the use of neuronal tracers, which are substances that, once injected in a brain region, are captured by the neurons and/or by the terminals of nerve cells, and are transported along the neuronal axon up to other brain areas. With this technique we can trace the information flow towards and from the injected region. In other words, we can discover the hard-wired connections between different modules performing a certain job.
As shown in Figure 2, we found a pathway connecting area V6A with both visual and motor cortices. The visual input to V6A derives from area V6, a higher order visual area of the dorsomedial visual stream directly connected with the primary visual area V1 [6]. Area V6A is also linked, directly, with the dorsal premotor cortex [7,8,see 9

for a review]. Therefore, there is a short route from vision to action (V1-V6-V6A-PM cortex) which is part of the so called dorsomedial visual stream, and which is thought to be useful for the on-line control of hand action [5].
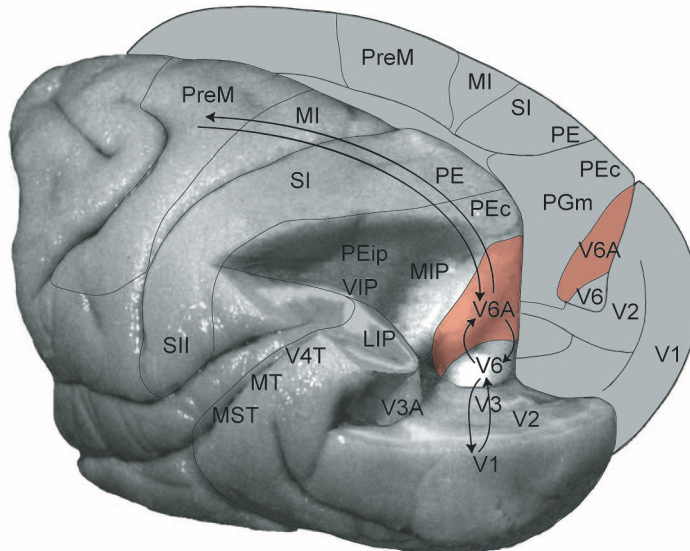

Fig. 2. The dorsomedial visuomotor pathway.
Arrows indicate anatomical connections between different cortical areas. There is a dorsomedial visuomotor pathway connecting the primary visual area (V1) with the premotor areas of the frontal cortex.
Other details as in Figure 1.

All these cortical connections are strictly bidirectional, that is area V6A receives visual information from area V6, but also sends information to this same area; similarly, area V6A sends information to the premotor cortex, but also receive information from it. It is a cortical loop that includes visual, visuomotor, and motor areas. Area V6A is one of the areas nestled in this loop.

As can be inferred by its connections, area V6A has both visual and motor properties, features which can be useful for the visual guidance of prehension. These functional properties of V6A neurons have been investigated in a series of electrophysiological studies, summarized hereafter.

Visual Neurons Able to Localize Objects in Space

Physiologists use the term "receptive field" (RF) to indicate the region of visual field from which a visual neuron receives visual information: the RF of a visual neuron is its window on the world. Contrary to what is generally thought, this window is not able to localize an object in space, because the RF moves with the eyes (being a part of the retina) and therefore explores different spatial locations according to the direction of gaze.

In area V6A there are visual cells in which the visual response (the response to the visual stimulation of the RF) is modulated by the direction of gaze [10]. These

neurons are able to code the location of objects in space because they discharge differently to the same object according to its spatial location.
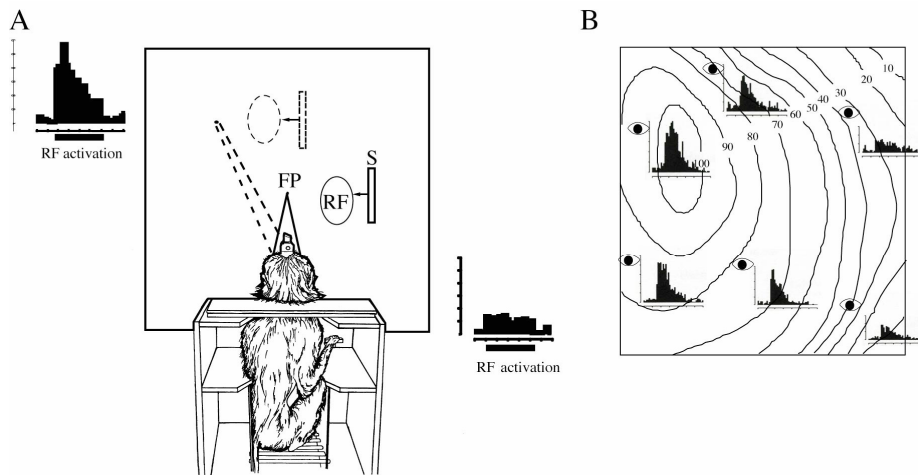

Fig. 3. Encoding of visual space by a gaze dependent visual neuron.
A. Experimental set-up and visual responses of a gaze-dependent visual cell. The square represents the screen in front of the animal. FP is the fixation point of the monkey, RF the receptive field of the neuron, and S visual stimulus used to activate the cell (the stimulus was moved leftwards across the RF). The histogram to the right of the screen is the response of the cell when its RF was activated while the animal gazed at the centre of the screen. When the monkey directed its gaze to the top left part of the screen (dashed lines), the RF of the cell moved to the top part of the screen too. The same stimulus as before across the RF in this new screen position evoked a good response (displayed to the left of the screen). Thick lines under neural responses indicate the stimulation time.
B. Gaze modulation in a V6A gaze-dependent visual cell. The square represents the screen. Six different visual responses are shown, evoked by stimulating the RF of the cell with the same stimulus, while the gaze was directed towards 6 different directions (6 eye symbols). Curved lines are iso-excitability lines linking together spatial locations where the visual responses were the same. The cell encoded the visual space in frequency of discharge: when the stimulus activated the RF on the top left corner of the screen it evoked the maximum discharge frequency (100%) from the cell; when it activated the RF on the right top or bottom corners it evoked a very poor response (10%) from the cell.

Figure 3A shows an example of this gaze-dependency of visual responses. When the animal gazed at the center of the screen, we found a good visual response when the right part of the animal's visual field was stimulated. This meant that the "window" (the RF) of this neuron was located there. When the fixation point was displaced in another location, for instance in the top left corner of the screen, the same RF stimulation as before evoked a neural response much stronger than before. How could this happen? Evidently this cell was informed about the type of visual stimulus that activated its receptive field, but it was also informed about where the eyes were directed. Combining the information coming from the retina with that on the direction

of gaze, different visual responses can be obtained according to the direction of gaze (gaze-dependent visual cell).

Figure 3B shows the analysis of gaze modulation in a V6A cell where a high number of gaze locations were tested. Curved lines link together spatial locations where the visual response were the same (iso-excitability lines). To obtain these data, we required the animal to fixate many different locations, thus displacing the neuron's receptive field on the screen many times. Each time we displaced the fixation point, we stimulated the RF with the same visual stimulus, obtaining a full field analysis of the neuronal visual responsiveness according to different angles of gaze. Different visual responses were obtained according to the direction of gaze. In other words, this type of cells transforms different spatial positions (those of the RF when the animal gazed at different locations) in different frequencies of discharge according to the direction of gaze. So they can inform us about the spatial location where the object is. This information can be used by the brain for many different purposes. Among them, that of directing the hand towards an object to be grasped.

We also found that in a minority of V6A neurons the RF remained stable in space despite changes in eye position. This finding contrasts dramatically with the behaviour of typical visual neurons, in which the RF is firmly anchored to the retina (being physically a part of it) and therefore move through space in tandem with the eyes (like for the neuron shown in Figure 3). The new type of visual cells receives (and encodes) visual information from different parts of the retina depending on the direction of gaze, but from a constant part of the visual space. We called them "real-position" cells [11]. Evidently, in the real-position cells, the gaze signal is used to gate the retinal locations from where visual information are picked up. This visual transformation, that has been then described also in other cortical areas of the parietal and frontal cortices [12,13], appears early in the dorsomedial visual stream in area V6A.

A: same retinotopic position
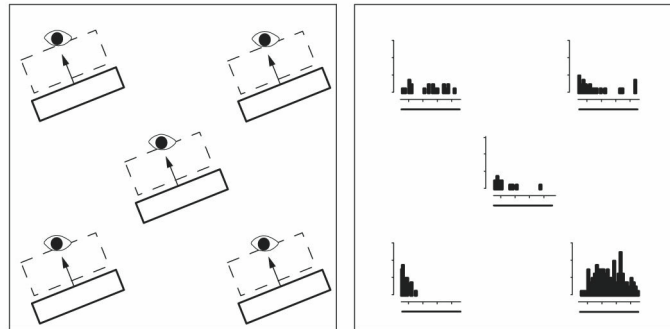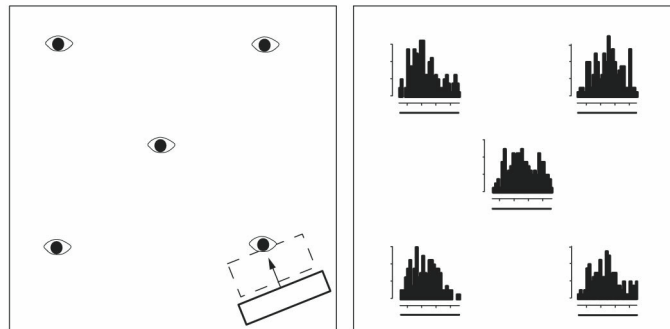

B: same spatial position

Fig. 4. Encoding of visual space by a real-position cell.
Neural responses of a 'real-position' cell to the visual stimulation of the same retinotopic location (A) or the same spatial location (B), while the animal looked at different screen positions. Each large square represents the screen in front of the animal. *Left*: experimental paradigm. Fixation-point locations on the screen are indicated by eye symbols. Visual stimuli (full line rectangles) were moved across the receptive field (dashed line rectangles) in the direction indicated by the arrow. *Right*: Neural responses to visual stimulations reported at fixation point locations. Thick lines under neural responses indicate the stimulation time. Scales are 4 spikes per vertical division, and 300 ms per horizontal division. Note that there is a visual response only when the visual stimulus is in the right bottom corner of the screen, irrespective from the direction of gaze.
Other details as in Figure 3. Modified from Galletti and Fattori [14].

Figure 4 shows an example of such a type of cell. This cell had a visual RF just below the fovea. The visual stimulation of the RF evoked a good response from the cell when the animal looked towards the bottom, right part of the animal's field of view, whereas the stimulation of the same retinotopic position was not effective when the animal looked towards all the other spatial locations (Fig. 4A). As shown in the Fig. 4B, if the stimulus was on the bottom, right part of the animal's field of view, the cell was always strongly activated, no matter where the animal was looking at. In other words, the RF of this cell did not move in tandem with the eyes as in any other visual

neuron. The cell encoded a specific part of the field of view regardless of the direction of gaze.

Neurons of this type encode *directly* the visual space. Each real-position cell encodes a different spatial location according to the spatial coordinates of its visually-responsive region. The cell in Figure 4 encodes the bottom right part of visual space. When this cell discharges, it means that the object activating the cell is in that particular region of the visual space, no matter where the animal was looking at.

A robot having to manipulate different objectes placed in different positions around it or having to select the target of its actions according to its position in space could of course benefit from a mechanism like that of real-position cells. In addition to be used to direct movements towards visual targets, the output of real-position cells could be used to direct selective attention to relevant points in space for acquisition of stimuli in the immediate environment, either by gaze or manual reaching. To this regard, it is worthy noticing that when we reach toward a target that suddenly appears in the peripheral visual field, not only does the arm extend toward the object, but the eyes, head, and body also move in such a way that the image of the object falls on the fovea. Because the eyes start to foveate the object while the hand is still moving, the reaching target changes its retinal location from its appearance in the visual field (peripheral location) till the end of reaching execution (foveal location). Nevertheless, the hand goes straight towards the target, as whether the motor center controlling the arm movement 'knew' in advance the final position to be reached out in spatial coordinates. We suggested that area V6A, and in particular the real position cells of this area, could play an important role in all these visuomotor transformations [14].

Somatosensory Neurons Monitoring Arm Position in Space

The humanoid robot dealing with the dishwasher (and ourselves in similar countless actions that we perform throughout the day) must take into account the position of arm in space and with respect to the torso to correctly guide an arm movement. If for instance the robot has the arm near the torso, it has to extend it in order to grasp the dish on the table; but if it starts the movement from a position reached in a previous action, the movement could be different. For example, if it starts the reaching movement with the gripper inside the dishwasher, it could need to adduct and flex the arm in order to grasp the dish on the table.

Which are the brain's sources of information about the position of the arm? The most important is the so called "proprioception", that is information coming from proprioceptors located inside the arm, giving the internal feeling of the limb position. The same that we could feel when, with the eyes closed, we try to locate our arms or fingers in space. Proprioceptive information arises from receptors that signal the stretch of muscles or the angle of joints. This information is carried by sensory fibers that reach the primary somatosensory cortex (depicted in blue in figure 1), and from there several other cortical areas of the superior parietal lobule, including area V6A [15]. Fig. 5 shows the distribution of V6A proprioceptive neurons: note that they are located only in the upper limbs. V6A contains also tactile neurons, that is neurons informed about touches of the hair or the skin: note that they are located only in the upper limbs and in parts of the trunk adjacent to the limbs (see Fig. 5). In summary, area V6A is informed about position in space of the arms as well as their interaction (contact) with objects in extrapersonal space.
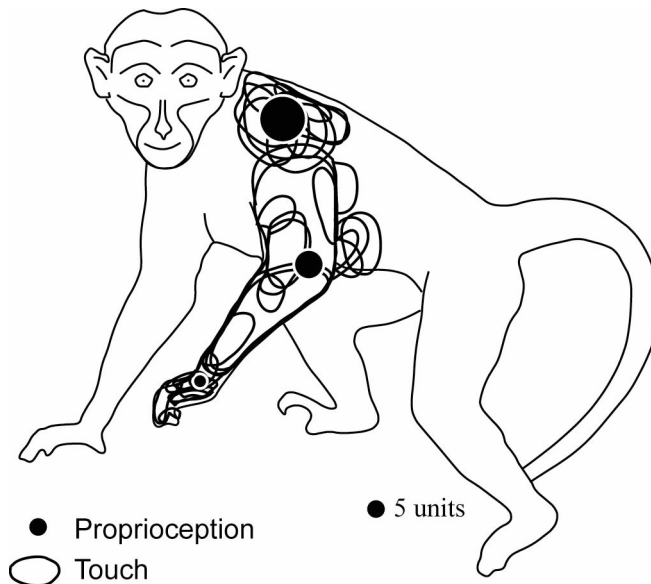
Fig. 5. Somatosensory representation by V6A neurons.
Dots: proprioceptive V6A neurons modulated by the rotation of a joint. The modulating joints are indicated by the dot location. The size of the dot is proportional to the number of modulated units. Continuous lines: extent and location of tactile receptive fields of V6A neurons. In V6A, body representation is largely incomplete and the representation of the arm is emphasised. Modified from Breveglieri et al [15].

Note that the somatic representation in V6A is different with respect to that of the typical cortical somatosensory areas, as in V6A the somatic representation is restricted to the upper contralateral limb. The fact that only the arm is represented in area V6A suggests that this region is involved in the control of arm movements. Proprioceptive cells could provide useful information about the spatial position of arm and hand while performing different hand-object interactions. Tactile receptive fields located on the arm and hand could be useful in recognizing the physical interaction between the moving arm and the environment, or between the hand and the object that it is grasping. All these information confirm us the actual location and status of the arm, and in particular the ongoing interaction between the hand and the grasped object.

Neurons Encoding Planning and Execution of Reaching Movements

A direct involvement of area V6A in arm movement execution has been demonstrated by the use of a specifically designed reaching task. It is sketched in figure 6A.
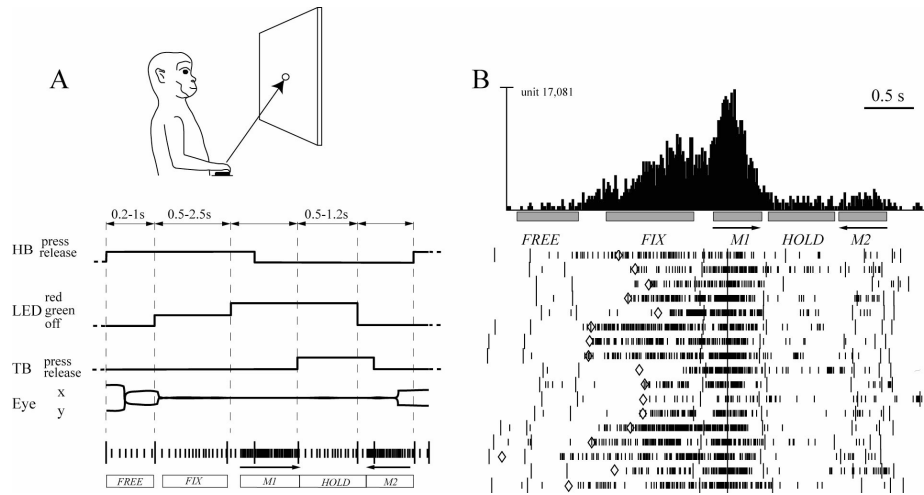
Fig. 6. Reaching activity in a V6A neuron.
A. The reaching task. *Top*: Scheme of the experimental set-up. Reaching movements were performed in darkness, from a home-button (black rectangle) towards a target (open circle) located on a panel in front of the animal. *Bottom:* Time course of the task: the sequences of status of the home-button (HB), target button (TB), and of the colour the target button (LED) are shown. Lower and upper limits of time intervals are indicated above the scheme. Under the scheme, typical examples of eye-traces (X and Y components) and neural activity during a single trial are shown. Short vertical ticks are spikes. Long vertical ticks among spikes indicate the occurrence of behavioural events (markers). From left to right, the markers indicate: trial start (HB press), target appearance (LED light-on green), go-signal for outward movement (green to red change of LED light), start and end of outward movement (HB release and TB press, respectively), go-signal for inward movement (LED switching off), start and end of the inward movement (TB release and HB press, respectively), and end of data acquisition.
Rectangles under neural activity indicate the time epochs referred to behavioural events. FREE: reference activity at rest; FIX: delay preceding reaching movement where gaze direction and arm movement are constant; M1: outward reaching, indicated by the arrow pointing to the right; HOLD: time of hand holding on the reached target; M2: inward reaching, indicated by the arrow pointing to the left.
B. Example of a V6A neuron coding planning and execution of reaching movements. Neural activity is shown as cumulative time histogram and as raster activities. Diamonds in raster activities indicates the onset of fixation of the reaching target. Cell's activity is aligned with the onset of forward arm movement (M1).
Scales: vertical bar on histogram: 140 spikes/s; other details as in Figure 3. Modified from Fattori et al [4].

In the task, the hand performs a reaching movement from a position near the body to a position in the peripersonal space in front of the body, trying to reproduce under controlled conditions the reaching movements performed in every day life when we reach out for objects.
The first controlled condition in the task is that the eyes are fixed in a position (the fixation LED), which represents also the goal of the reaching movement. The second controlled condition is that the arm always starts the movement from a button near the chest and reaches a target placed on a panel in front of the monkey with a direct,

ballistic movement that follows a precise time sequence (summarized in figure 6A) decided by the experimenter. The last controlled condition is that the task is executed in complete darkness, with the only exception of the fixation light, which was a LED the brightness of which was reduced so that it was barely visible during the task. This was chosen to avoid to evoke visual activation during the execution of the task other than the fixation point. It is evident that in these experimental conditions any neural modulation during the task must be ascribed to arm-related activity.

Using this task, we found that many neurons in V6A were modulated during the preparation and execution of reaching movements [4]. An example of these reach-related cells is shown in Figure 6 B. This neuron strongly discharged during the execution of the reaching movement toward the target (M1). The neuron shows also an increase in its firing rate in the delay preceding the movement (FIX period). In this epoch, the monkey is already fixating the target of reaching and no arm movement is occurring. Therefore, the neural discharge can not be explained by arm-movements nor by oculomotor behaviour. We suggested that the neural discharge is a preparatory signal for the impending reaching movement [4].

The figure 7 shows two V6A reach-related cells studied with the same task. The first (Fig. 7A) is activated by movements of the arm directed toward the visual target (M1, outward reaching); the second, for arm movements directed away fron the target, towards the body (M2, inward reaching).
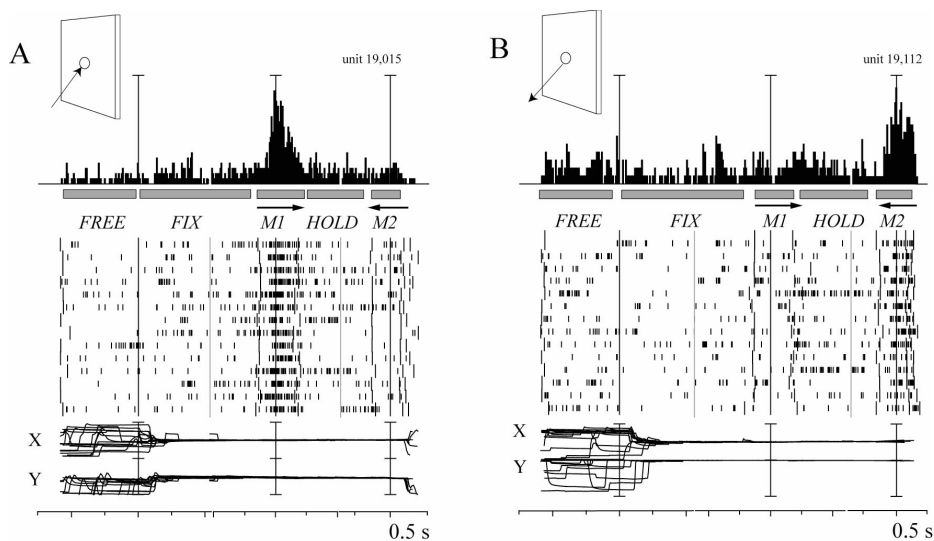

Fig. 7. Two V6A neurons modulated by reaching movements.
A: Neuron modulated by outward reaches. From top to bottom: cumulative time histogram of neural activity, time epochs, raster displays of impulse activity, recordings of X and Y components of eye positions. Neural activity and eye traces are aligned three times for each neuron: with the LED appearance (1st), with the onset of outward (2nd) reaching movements, and with the onset of inward (3rd) reaching movements.
Peri-event time histograms: binwidth = 15 ms; scalebar = 100 sp/s. Eyetraces: scalebar = 60 degrees.
B: Neuron modulated by inward reaches.

Scalebar in peri-event time histograms: = 65 sp/s (**B**).
Other details as in Fig. 6. Modified from Fattori et al [16].

To reach the dish on the table, the humanoid robot has to know in which direction to move the hand. A variance of the task allowed us to test whether the direction of reaching movements influenced the discharge of V6A reaching neurons. Monkeys were required to reach visual targets placed in different spatial locations while gazing at them. In other words, the animal performed reaching movements toward different spatial locations while maintaining the target of reaching under foveal control. We found that the direction of reaching strongly modulates the activity of V6A cells [16]. An example of this behaviour is shown in Figure 8.
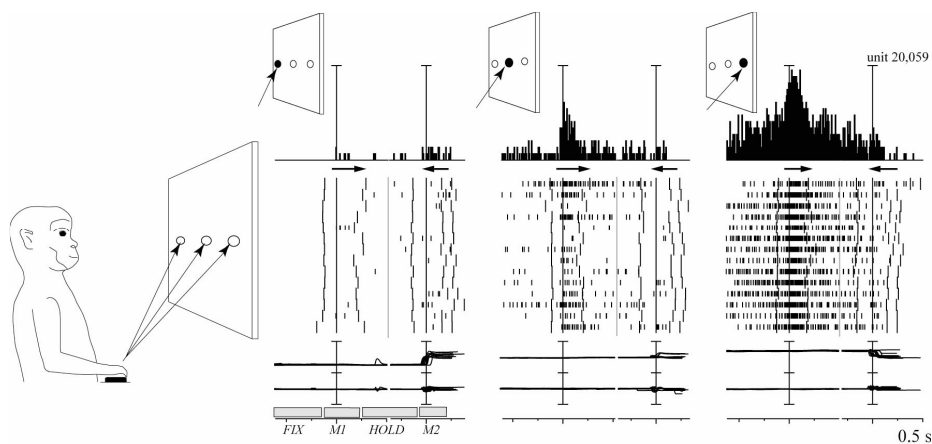

Fig. 8. V6A neuron coding directions of reaching.
Neuron preferring rightward M1 movements and rightward gaze directions.
Sketches on the left and top illustrate the different directions of reaching tested in this neuron. Neural activity and eye-traces are aligned twice in each inset, with the onsets of outward (1st) and inward (2nd) reach movements, respectively. The mean duration of epochs FIX, M1, HOLD, M2 is indicated in the bottom left inset.
Scalebar in peri-event time histograms: = 70 sp/s. All other details as in Fig. 7.
Modified from Fattori et al [16].

The unit in Figure 8 discharged for reaches directed to the visual target only when it was straight ahead or in the right part of space. The cell was not activated at all by reaching movements directed to the same target placed in the left part of space. The neuron was also strongly affected by the direction of gaze, being the cell strongly activated when the animal looked straight ahead or to the right without performing any arm movement (see activity during FIX epoch). This cell signalled the occurrence of both rightward ocular and reaching movements. Other V6A cells signalled only the direction of gaze or the direction of reaching movement. In the whole, V6A cells were able to encode the entire set of directions we tested in the workspace [16].

Neurons Encoding the Grasping Phase of Prehension

The act of prehension includes the reaching movement, that is the transport of the hand towards the object to be grasped, and grasping movements, which involve more distal parts of the arm, as the wrist, hand and fingers. Recently, we have began to study whether V6A is involved in the control of grasping, by training monkeys to perform reach-to-grasp movements under controlled conditions [17]. In Fig. 9, the behaviours of a cell to reaching and to grasping movements are compared. The direction of reaching was the same (straight ahead) in reach-to-point (Fig. 9A) and reach-to-grasp (Fig. 9 B) tasks, but in the latter the monkey had to preshape the hand to grasp an handle and to flex its fingers to secure the grasp of the object. Therefore, any difference in neural activity in the reach-to-grasp with respect to reach-to-point task must be attributed to the grasping action, as the transport phase of reaching movement was the same in the two experimental situations. This cell was not activated during the execution of the reach-to-point movement, but was excited during reach-to-grasp action. In this action, the finger extended to embrace the handle and then flexed to acquire it. Many V6A cells behaved like that shown in Figure 9, and V6A seems to have a role in coding also distal, besides proximal, components of the act of prehension.
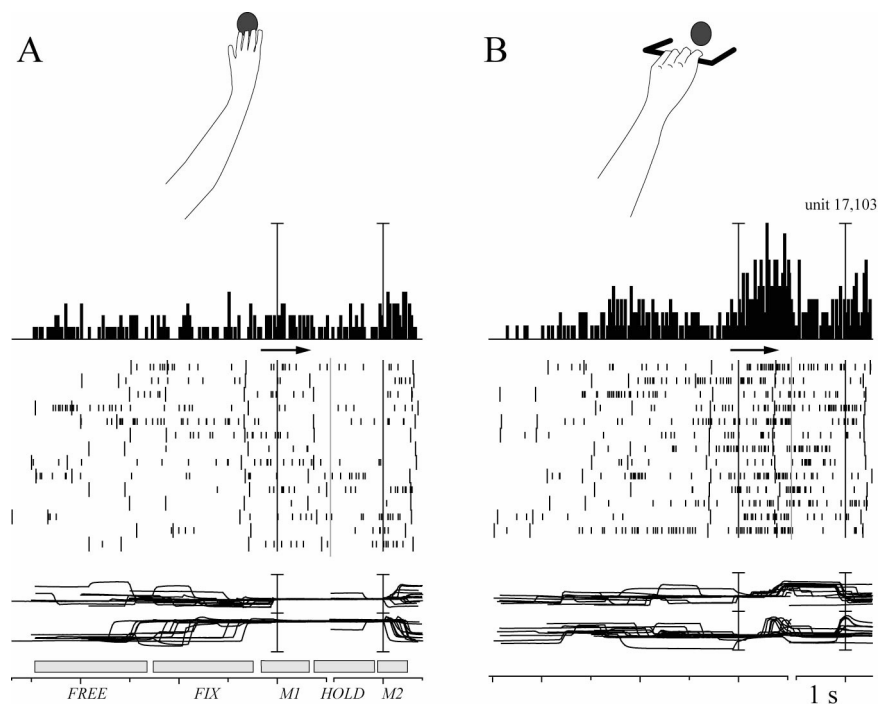

Fig. 9. Reach-to-point and reach-to-grasp activities in a V6A neuron.
Top: sketch of the final hand position in the reach-to-point (A) and reach-to-grasp (B) tasks. *Bottom*: Activity has been aligned twice, with the onset of forward and backward arm movements, respectively. Peri-event time histograms: binwidth = 20 ms; vertical bar on histograms: 55 spikes/s; eye traces: 60 degrees/division. All other details as in Figure 6.

Note that the cell was clearly more activated in the reach-to-grasp than in the reach-to-point task, and the handle in (B) was in the same spatial location as the LED in (A). Therefore, the arm movements performed in (B) and (A) were similar in trajectory amplitude and direction, but only in (B) they did include the grasp.
Modified from Fattori et al [17].

In summary, the picture emerging from data reviewed here is that area V6A is a cortical region involved in the control of many components of the act of prehension under visual guidance: in localizing objects in space, in sensing where our arm is and what our hand touches, in transporting the hand towards the target object, in coding the direction of reaching and in adapting the hand to the object features. Area V6A could be useful in the online control of arm movement by elaborating sensory inputs and motor outputs to represent the internal body state for the purpose of sensorimotor integration.

Links to Robotics Research

The design of artificial systems having efficient reaching and grasping capabilities is currently a very hot topic in the field of robotics. New impetus can be given to this area by examining the working principles of cortical area V6A being directly involved in the solution of the underlying tasks. In the following we highlight some working principles of V6A [5] that worth consideration in robotics research, aiming at improving the efficacy of contemporary robotic systems.

At first, we note the specialization of V6A in processing sensory information coming mainly from the peripersonal space of the animal. This type of limited spatial perception, filters environmental sensory input, providing to the relevant motor system only the information that can be useful during action.

Furthermore, the simultaneous utilization of many different coordinate systems for encoding information, seems to be necessary for efficient reaching and grasping movements. In particular, V6A is directly involved in the transformation of retinotopic stimuli to the executional motion direction, encoding how the same information is referenced in all the intermediate coordinate systems. In other words, it is important to combine information referred to both an action-irrelevant coordinate system like the retinotopic, and also an action specific coordinate system, as it is the case with arm motion-direction cells and with cells like the real-position cells that code directly the visual space. This is necessary for making direct and effective modifications to the executed action when sensory changes are identified.

Additionally, the reciprocal connectivity of V6A, with both the sensory and the motor areas, seems to be very important. Specifically, the brain pathway responsible for reaching and grasping movements does not operate in a feed-forward way, but it rather follows recurrent connectivity in all stages of information processing. During every phase of the action, multi-modal information is integrated in order to confirm that the execution proceeds in the appropriate way.

Finally, the encoding of both hand and visual information in the same associastive brain area implies that in producing artificial intelligent systems that perform prehension actions, these two information must operate in a coordinated manner rather than in isolation from one another.

In addition to the above general principles that could be proved beneficial for the design of novel robotic systems, neurophysiological studies can provide further input to robotics research. This can be done in a first approach by abstracting higher level cognitive information addressing the connectivity of brain areas and the type of information they convey to each other. Furthermore, in a more detailed and practical level, biological data can be utilized by well known computational methods designing artificial systems that approximate the structural and functional characteristics of biological ones. Initial attempts towards this brain approximation direction have been done in [18]. Robotics and neurophysiology could also be met in a new research field where bioelectrical signals obtained by single cell recordings are utilized for driving robotic devices, formulating a new alternative approach on Brain-Computer Interface studies [19].

Conclusions

Neural behaviours like those here described for V6A have been described in many areas of the brain, but what is unique for V6A so far is that this region contains *all* these neural behaviours. Cells encoding the visual space cohexist in V6A with cells controlling grasping movements and with somatosensory cells signalling what our arm is doing. We are currently working on how these different neurons interplay together.

Area V6A can be a good model and could be "copied" in building the cognitive architecture of artificially-intelligent systems that have to interact with objects, localize them, direct toward them their arm and grasp them with their gripper.

Combing the neurophysiological expertise with the engineering and computer science ones can be a way to implement the evolution of humanoid robots performing more efficiently the dishwasher task and even harder tasks like those of interacting with human beings, exchanging objects with them, and acting in an ever changing environment.

Aknowledgements

References

1.   Galletti C, Fattori P, Battaglini PP, Shipp S, Zeki S. Functional demarcation of a border between areas V6 and V6A in the superior parietal gyrus of the macaque monkey. Eur J Neurosci 1996; 8(1):30-52.
2.   Galletti C, Fattori P, Kutz DF, Gamberini M. Brain location and visual topography of cortical area V6A in the macaque monkey. Eur J Neurosci 1999; 11(2):575-582.
3.   Galletti C, Fattori P, Kutz DF, Battaglini PP. Arm movement-related neurons in the visual area V6A of the macaque superior parietal lobule. Eur J Neurosci 1997; 9(2):410-413.

4.   Fattori P, Gamberini M, Kutz DF, Galletti C. 'Arm-reaching' neurons in the parietal area V6A of the macaque monkey. Eur J Neurosci 2001; 13(12):2309-2313.

5.   Galletti C, Kutz DF, Gamberini M, Breveglieri R, Fattori P. Role of the medial parieto-occipital cortex in the control of reaching and grasping movements. Exp Brain Res 2003; 153(2):158-170.

6.   Galletti C, Gamberini M, Kutz DF, Fattori P, Luppino G, Matelli M. The cortical connections of area V6: an occipito-parietal network processing visual information. Eur J Neurosci 2001; 13(8):1572-1588.

7.   Matelli M, Govoni P, Galletti C, Kutz DF, Luppino G. Superior area 6 afferents from the superior parietal lobule in the macaque monkey. J Comp Neurol 1998; 402(3):327-352.

8.   Shipp S, Blanton M, Zeki S. A visuo-somatomotor pathway through superior parietal cortex in the macaque monkey: cortical connections of areas V6 and V6A. Eur J Neurosci 1998; 10(10):3171-3193.

9.   Galletti C, Fattori P, Gamberini M, Kutz DF. The most direct visual pathway to the frontal cortex. Cortex 2004; 40(1):216-217.

10.   Galletti C, Battaglini PP, Fattori P. Eye position influence on the parieto-occipital area PO (V6) of the macaque monkey. Eur J Neurosci 1995; 7(12):2486-2501.

11.   Galletti C, Battaglini PP, Fattori P. Parietal neurons encoding spatial locations in craniotopic coordinates. Exp Brain Res 1993; 96(2):221-229.

12.   Fogassi L, Gallese V, Fadiga L, Luppino G, Matelli M, Rizzolatti G. Coding of peripersonal space in inferior premotor cortex (area F4). J Neurophysiol 1996; 76:141-157.

13.   Duhamel JR, Bremmer F, BenHamed S, Graf W. Spatial invariance of visual receptive fields in parietal cortex neurons. Nature 1997; 389:845-848.

14.   Galletti C, Fattori P. Posterior parietal networks encoding visual space. In The Cognitive and Neural Bases of Spatial Neglect. Karnath H-O, Milner AD, Vallar G, (editors). Oxford, New York: Oxford University Press; 2002. pp. 59-69.

15.   Breveglieri R, Kutz DF, Fattori P, Gamberini M, Galletti C. Somatosensory cells in the parieto-occipital area V6A of the macaque. Neuroreport 2002; 13(16):2113-2116.

16.   Fattori P, Kutz DF, Breveglieri R, Marzocchi N, Galletti C. Spatial tuning of reaching activity in the medial parieto-occipital cortex (area V6A) of macaque monkey. Eur J Neurosci 2005; 22(4):956-972.

17.   Fattori P, Breveglieri R, Amoroso K, Galletti C. Evidence for both reaching and grasping activity in the medial parieto-occipital cortex of the macaque. Eur J Neurosci 2004; 20(9):2457-2466.

18.   Maniadakis M, Hourdakis E, Trahanias P. Modeling Overlapping Execution/Observation Brain Pathways. accepted for publication in the International Joint Conference on Neural Networks (IJCNN) 2007.

19.   Birbaumer N, Weber C, Neuper C, Buch E, Haagen K, Cohen L. Physiological regulation of thinking: brain-computer interface (BCI) research. Progress in Brain Research, vol 19, pp 369-391, 2006.