

Chapter 7

An Ever-Developing Research Framework

This chapter presents a number of issues and developments that could not fit in the presentation of the model in Chaps. 4, 5 and 6. Some aspects are controversial and need additional neuroscience data to be modeled, others would need a different robotic setup to be properly tested. Some ideas have simply not been implemented yet, or have been implemented only partially, and thus do not fit in the main modeling framework.

In Sect. 7.1, the sort of visuomotor transformations performed by AIP are further discussed and suggestions for additional modeling provided. Section 7.2 presents a detailed modeling proposal for the interaction between the streams. A research work performed on the subject in collaboration with Blaise Pascal University is summarized. Finally, in Sect. 7.3, the fRI interface for visualizing the activity of a robot as in a simulated fMRI experiment is presented. In general, implications for further studies in neuroscience, computational modeling and robotic applications are discussed.

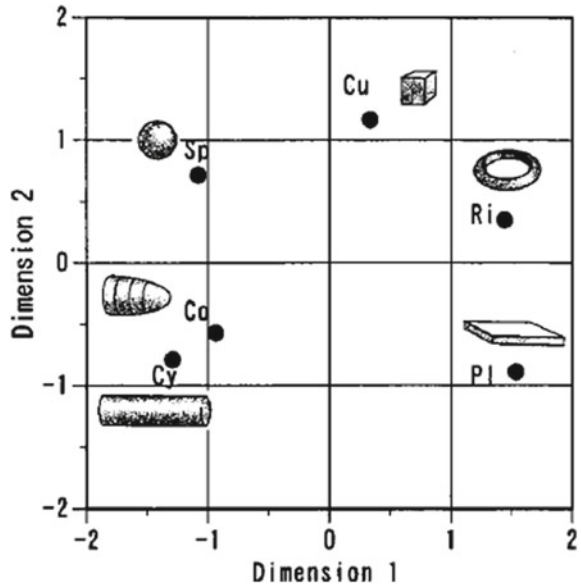
7.1 Purely Visual and Visuomotor Transformations in AIP

The proposal for generating suitable hand configurations from visual data advanced in Sect. 6.2 is constrained by the implementation of other modules and by limitations of the robotic hardware. The job of AIP in grasp planning and execution is surely more complex and nuanced. All ventral stream information, such as weight or friction, and task related issues are left aside for the moment, and discussed in Sect. 7.2.

7.1.1 Visual-Visual Transformations

Object type neurons in AIP seem to encode 3D object geometry in a grasp-oriented way (see Sect. 2.3.2). Following the suggestions of Rizzolatti and Luppino (2001)

Fig. 7.1 Principal components of visual object representation for object type neurons of the anterior intraparietal sulcus AIP. From Murata et al. (2000)



and the experiments of Fukuda et al. (2000), they should perform a purely visual transformation of the SOS/AOS coding received from CIP. Figure 7.1, taken from Murata et al. (2000), represents the two principal components of the activation of AIP object type neurons during fixation of different target objects.

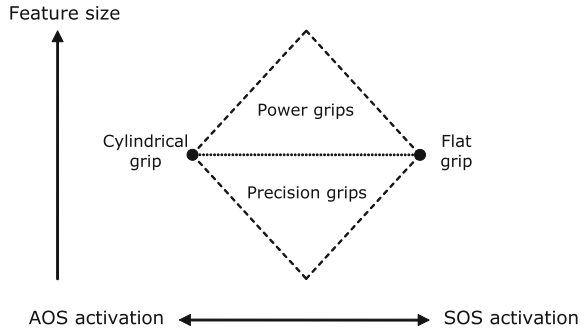
The authors performed the same mapping for object type neurons during grasping, and for non-object and motor type neurons. The first is very similar to the one displayed in Fig. 7.1, the other two are different but very close to each other. The shape distribution may be interpreted in many ways, but a first qualitative analysis suggests that the AOS/SOS distinction is approximately represented in the first dimension. It is less clear what object qualities are discerned by the second axis. There seems to be an important symmetry component, but also a curvature effect. Moreover, it is not clear how the extremely important aspect of object size enters the schema. In any case, there is in principle a direct mapping between this representation and the input coming from CIP.

A second, more complex transformation has to be performed for matching visual properties to hand configurations.

7.1.2 Visuomotor Transformations

The above data refer to experiments with macaques. Although the basic concepts are not expected to change, the greater dexterity of the human hand and the increased complexity of the human intraparietal sulcus suggest that the situation is more com-

Fig. 7.2 A basic 2D space of grip taxonomy



plex for human grasping. It is reasonable to assume that a representation similar to the SOS/AOS, although somewhat more elaborated, is used in the human IPS as well. Similarly, the graphs of Murata et al. (2000) probably show a simplified version of what could be found in human AIP. A simple proposal on which to build a theory of visuomotor transformations in human AIP is provided below.

In Fig. 7.2, a 2D space is depicted which jointly represents SOS and AOS activations and a basic grasp taxonomy. Such taxonomy is very likely a multidimensional joint space described by all possible combinations of joint angles, in which only the extreme cases can be clearly identified with recognizable basic hand shapes. In the proposal of Fig. 7.2 the basic grips of the taxonomy are, on the vertical direction, the full-hand or power grip and the smallest pinch or precision grip. In the horizontal direction, there are the ideal flat grip in which only the metacarpal-finger phalanges are flexed, so that all fingers are parallel and opposed to the thumb, and the ideal involving or cylindrical grip, in which all phalanges are flexed and the hand closed in a fist. These two last grips correspond to the ideal maximum activation of SOS and AOS neurons, as the former is suitable to grasp a perfectly flat surface, and the latter a thin elongated shape.

Summarizing, the list of theoretical *extreme* grips from which all hand configurations derive are:

- flat grip: SOS neurons are dominant; predominant flexion of proximal phalanges, pad opposition between thumb and other fingers;
- cylindrical grip: AOS neurons are dominant; all phalanges are flexed, involving the object, finger pad and palm opposition;
- precision grip: strong activation of one or both kinds of orientation selective neurons; adapt for small features requiring thorough visual analysis, the thumb is opposing the index or middle finger, the other fingers can be used for support;
- power grip: limited activation of SOS and AOS neurons; full hand, spherical grip, maximum contact of fingers and palm, used for default when no other grips are considered appropriate, or if visual analysis is considered unreliable or incomplete.

All possible grasping configurations would thus be found inside the parallelogram, classified either as a precision or a power grip, with a continuous separation between the two, and also somewhere in between the involving and flat grips. Indeed, the four ideal grasps are just abstractions, and it is reasonable to assume that the edges and corners of the parallelogram do not correspond to real grasping configurations. Moreover, whilst “pure” cylindrical grips are more easily associated to power tasks, opposition grips appear more dexterous, suggesting that there is no real symmetry as the graph would indicate.

From an ecological point of view, the plausibility of the proposed representation is supported by a sort of economy principle for grasping, according to which more general purpose and less precise grips do not need detailed visual analysis. In fact, small, precision grips probably need detailed information from both kinds of neurons, whilst power, full hand grips are likely to represent a default choice.

Unfortunately, this proposal cannot be tested at the current stage of development of the model. Firstly, as already pointed out, curvature and size coding of CIP neurons have not been properly characterized yet. Then, AIP studies did not analyze the same objects used for CIP. It would be very helpful for example if cylinders and parallelepipeds of the same size and proportion could be presented to CIP and AIP and their activations compared, to study the effect of curvature changes on the two areas. The same should be done for other types of objects, and the effect of size should be studied in a similar way.

Further limitations are posed by the robotic hand. In fact, the Barrett Hand does not allow for voluntary, independent movements of the finger phalanges, so that, unless for very large objects, the grip is practically always cylindrical. Moreover, palm opposition can not be performed properly, because there are no touch sensors on the palm which would detect object contact.

7.1.3 The Reaching and Grasping Action

The best solution to construct the visuomotor matching between visual data and hand shapes is probably to develop a robotic experimental framework in which suitability of hand shapes to visual data is gradually learnt, for example through a reinforcement learning process in which grasp stability is positively rewarded. Such framework would allow to analyze naturally emerging visuomotor transformations, and test the efficiency of different alternative visual representations. Bootstrapping for the learning process could be provided by basic postures identified through examples of human joint spaces extracted with a data glove.

The same postures could constitute an ideal starting point for building truly human-based motor primitives for the robot arm and hand. Lim et al. (2005) extract movement primitives from the analysis of human movements, and propose a method for joining them and implementing motions in robotic applications. Their guidelines, together with the experience provided by other related works (see e.g. Nori and Frezza 2005), could constitute the starting point for merging accurate visual analysis with

biologically plausible action execution. A framework of this kind would also be particularly suitable for monitoring of action execution through an implementation of the forward model/inverse model principle more accurate than the one proposed in Sect. 6.2.4.2. Such implementation could be done following the guidelines of Kawato (1999), Wolpert and Ghahramani (2000) and Miall (2003) and forward models can be learnt from experience as in Dearden and Demiris (2005).

Timing and coordination between action components, which are not dealt with in the model, would benefit from this sort of modeling improvement. For example, the correct coupling between the reaching and grasping movements is an issue that has not been considered, as often happens in robotics applications. This is instead a fundamental and largely studied aspect in human grasping, and various plausible models on the relation between reaching and preshaping have been developed (Shadmehr and Wise 2005). The hypothesis of parallel visuomotor channels for the transport and the preshaping components of the reach-to-grasp action is well recognized (Jeannerod 1999). Alternative models, such as the *multiple finger reaching* idea (Smeets et al. 2002), are not given much credit, due to the quantity and quality of evidence supporting the mainstream hypothesis (see e.g. Tanné-Gariépy et al. 2002; van de Kamp and Zaal 2007). In any case, the coupling between the two subsystems linking parietal and premotor cortex is tight, and they must share a common mechanism for coordinating with each other (Jeannerod 1999; Roy et al. 2002; Fattori et al. 2010). Various computational models of reaching and grasping coordination that might be suited to robotic implementation are available (Mon-Williams and Tresilian 2001; Jiang et al. 2002; Ulloa and Bullock 2003; Hu et al. 2005). Primates often perform coordinated eye and arm movements, contextually fixating and reaching towards nearby objects. Taking inspiration from such visuomotor mechanisms (Chinellato et al. 2010; Bosco et al. 2009), (Chinellato et al. 2011) designed and developed a model for learning and producing the coordinated control of gazing and reaching movements.

7.1.4 After Contact

A more immediate extension to the developed framework is the use of post-contact information for improving the reliability of the vision modules. In fact, after tactile adjustment, the exact position, orientation, and one of the object dimensions can be exactly measured, through proprioceptive feedback on the hand and arm state. These values can be compared to the initial estimations, and the error magnitude and sign of each measure memorized, in association with the object class. Even more, errors can be calculated for each one of the different estimators presented in Sect. 5.4.3. In this way, for each estimator a reliability function dependent on object size, distance and pose can be defined, and used in the following experiments. Human experiments support this proposal, as it has been demonstrated that cue weighting in slant perception can be modified by haptic experience (Ernst et al. 2000). The next-generation estimator will thus perform cue integration using both correlation and reliability, as it is done in the primate brain.

Summarizing, an improved modeling of the visual and visuomotor transformations performed in AIP should consider learning processes in which multimodal tactile and visual feedback is used to bias the matching between different representation levels.

7.2 A Tighter Interaction Between the Streams

Even though it is widely accepted that the dorsal and ventral streams tightly interact with each other, the mechanisms underlying such interaction are still largely under debate (Goodale 2008; Cloutman 2013). In the neuroscience review, two levels of direct integration between the streams were mentioned, one for the ventral connections of CIP and the second for those of AIP.

7.2.1 *Links Between CIP and the Ventral Stream*

Section 2.3.1.3 described the possible bidirectional links of CIP with ventral stream areas (Zanon et al. 2010; Perry et al. 2014). The dorsal use of information regarding object class was explicitly modeled in Chap. 5. On the other hand, the second step in the framework of Sect. 5.2.3, full object recognition, is not dealt with in the implemented system, and can be simplified and accelerated by dorsal input. Object recognition could rely for example on a chain code invariant representation as the one initially used for classification, and which revealed more suitable for single object identification than for class discrimination (see Sect. 5.4.2). Various researchers pointed out though that action-related information maintained in the dorsal stream is likely to play an important role in the object recognition process, as a set of possible affordances constitutes an additional way of identifying an object (Sugio et al. 1999; Shmuelof and Zohary 2005). The SOS and AOS responsiveness found for the target object could be one possible format used by the dorsal stream to help the ventral areas in the recognition task. It is in fact very unlikely that two objects share the same SOS and AOS activations. CIP projections would thus provide the ventral stream with additional information for improving the reliability and speed of object recognition. For what concerns the representation of known objects, in their first years of development, human beings accumulate experience on properties such as color, texture, material, object identity, learning the likelihood of different relations among them. A working model of this recognition and generalization capacity should rely on a knowledge base founded on these properties (see e.g. the proposal of Metzinger and Gallese 2003).

There is a second ventral \rightarrow dorsal link that could involve intraparietal areas other than AIP. This projection would occur after object recognition, and would provide the dorsal stream with the exact object size as memorized in ventral areas. In fact, object identification would allow to recover specific stored knowledge on object dimensions

that can be used to resolve more easily and accurately the size/distance ambiguity. This mechanism is supported by several different studies comparing grasping accuracy using monocular and binocular data and different kinds of objects (Loftus et al. 2004). For example, it has been shown that proprioceptive cues such as vergence and accommodation are relied upon especially for novel objects, suggesting that for known objects retinal data, inherently ambiguous otherwise, are predominant (Mon-Williams and Tresilian 1999).

7.2.2 Links Between AIP and the Ventral Stream

The second stage of integration between the streams refers to the direct links between ventral areas and AIP (Zanon et al. 2010; Verhoef et al. 2011), which have been repeatedly pointed out in the book. An explanation of how properties related to the object identity would affect the selection of grasp features and contact points have been provided in Sect. 6.2.2, but the proposal has not been implemented in all its details yet. As explained, a higher confidence in the object recognition/classification process reflects in a stronger influence of past grasping experiences, whilst a more uncertain recognition leads to a more exploratory behavior, giving more importance to actual observation. Recognition of object identity can affect dorsal processing at three levels.

The first level, described above, is the ventral contribution to object size and distance estimation. At the second level, the ventral stream can provide the dorsal with the exact object weight, roughness, compliance, and consequently orient the criteria employed for action selection, as described in Sect. 6.2.2. Hand preshape, target contact points and initial grasping force would be contextually defined according to the ventral information (Perry et al. 2014). The third and final level refers to the third stage of object recognition (Sect. 5.2.3), in which grasping has to be executed on a familiar object. It can be supposed that in this case the motor coding of a grasping action is already associated with the object. In fact, such patterns has been observed for tools, which seem to elicit dedicated learnt motor representations (Creem-Regehr and Lee 2005; Johnson-Frey et al. 2005; Valyear et al. 2007). While in the previous stages there was a variable balance between recalling and exploration, for this case the process of grasp planning is reduced to its minimum. Only object pose and distance have to be estimated, as the preshape movement, and the expected contact with the object are recovered from previous experiences.

The implementation of this mechanism has to be based on two modeling elements already cited above: an appropriate knowledge base of objects and a suitable vocabulary of motor primitives that can be associated to such objects. At this level of detail in the modeling of grasping behaviors, the task could not be disregarded, and the mentioned object knowledge base should include their possible utility. Therefore, different tasks can be associated with different motor programs, and a motor program can be associated to a given task even for different objects. If a hammer is not available, another tool will be used “as a hammer”, emphasizing that the motor program

is associated to the task, and can be transferred to novel objects. The final goal is a three-way model in which visuomotor coding, object identity and task requirements modulate the level of interaction between the streams (Plewan et al. 2012; Tankus and Fried 2012; Wokke et al. 2014).

The additional information provided by the tactile feedback upon contact of the hand with the object is critical in this process. The only way to learn the exact object size is through proprioceptive feedback after grasping, and the same happens for its weight and compliance. The above mentioned method for learning the reliability of the various visual cues in different conditions can hence be extended to associate with each object properties that are relevant for grasping purposes. This can be achieved through a cross-modal object representation in which visual and tactile information complement each other, and which is directly related to the task to perform. A representation of this kind is likely maintained in the human LOC (Amedi et al. 2001; Binkofski et al. 2004).

7.3 fRI, Functional Robotic Imaging: Visualizing a Robot Brain

In this section, an auxiliary tool aimed at improving the integration between neuroscience, computational modeling and robotic systems is presented. This tool is the fRI (functional Robotic Imaging) interface for the functional visualization of a robot activity, described in detail in Chinellato and Pobil (2008).

The fRI interface associates each task performed by the robot to a brain area and visualizes its activation on a brain image, similarly to what happens in fMRI experiments (see text box on fMRI). The information flow can thus be monitored at a very high level, and especially non-roboticists can benefit from this kind of functional visualization. The scanning of the “robot brain” is much easier, faster and cheaper than real imaging, and far from representing an alternative to real experiments, it may help researchers in two important ways. First, fRI can be used to check in advance the appropriateness of experimental protocols, reducing expensive and complicate preliminary tests with human subjects (Culham 2006). Second, it represents a way for comparing, and validating, possible explanations of experimental results derived from different models. The ambitious goal is to make the tool useful for both the definition of experimental protocols and the interpretation of results according to alternative models. The tool is suitable for models that are applicable to robotic setups while maintaining a strong functional resemblance with brain areas. In this way, the rigorous model design is likely to represent an ideal inspiration source for planning completely new experiments.

An additional feature of the fRI tool and the associated modeling architecture is the possibility of performing “impossible experiments”. As mentioned in Chap. 2, neuroscience theories often derive from observations done on neurally-impaired people. Logically, such experiments cannot be reproduced, neither it is possible to decide

beforehand the type of brain damage on which to investigate. If properly implemented, a layout as the proposed one would allow for such critical experiments.

The fRI approach presents two main differences with the only related work in the literature (Arbib et al. 2000), which deals with large computational models and the possibility of simulating brain imaging experiments with them. First, the proposed modeling paradigm is focused on the function of computational modules, and not on their structure or on particular implementation techniques. The second fundamental difference is the application-oriented stance of the current approach, which is designed to be implemented on a robotic setup, and not only computationally.

The part of the model dedicated to extract and map visual features to hand configurations, exposed in Sect. 6.2 and further discussed in Sect. 7.1, is used as a first testbed for showing how the fRI instrument works, and how it may constitute an additional tool for depicting the functioning of a relatively complex neural model.

7.3.1 Modeling Requirements

There are a number of restrictions for a model in order to be coupled with the fRI visualization tool. First of all, it has to be a functional model, implemented at the proper level of abstraction (see Sect. 4.2), and composed of various modules. The modules should be provided with the flexibility necessary for simulating different behaviors and skills through re-configuration, and not through re-programming. Only in this way can they be used to test theories and assumptions. This goal can be achieved using a distributed architecture of interconnected modules, which have to be simple and robust in order to allow easy modification of the data flow.

Recruitment between modules is driven by a set of connectivity rules and by the current data flow. A module corresponds to a neuronal population performing a certain function, and is associated with a modeled brain area, which can be composed of one or more modules. For example, there may be two modules for SOS and AOS activations upon visual presentation of a target object, and both modules would belong to area CIP. The rules that determine the connectivity of the set of modules represent a model of how the brain performs a given task. The projection of SOS and AOS activations to an AIP module representing object type neurons is an example of connectivity between modules. The pattern of activation of the different modules will thus depend on the programmed connectivity and on the input set.

For the recruitment of a module, it may be necessary to have more modules calling on it at the same time. Also, some modules could facilitate the activity of a specific module, others could inhibit it. For example, in a grasping task, the module which computes the distance of the object would inhibit grasp planning if the object is out of reach.

7.3.2 The fRI Interface

The purpose of the fRI interface is to visualize the actions performed by a robot as they were executed by a human subject during an fMRI experiment. The activity of the robot is thus displayed through a series of activations of brain areas, in a simulated fMRI analysis screen. The result is similar to what can be obtained after data analysis in a real fMRI experiment, like the one shown in Fig. 7.3.

From the list of implemented modules, and the relative brain areas, a library of locations is created, representing the position in the brain of the areas corresponding to the various modules available. Locations can be obtained from the literature, and are kept in Talairach coordinates, which allow an easy mapping on normalized anatomical images (Talairach and Tournoux 1988). For example, the anterior intraparietal sulcus AIP has been located with a 95 % confidence interval by averaging the results of different studies (Frey et al. 2005). Figure 7.3 represents the contrast

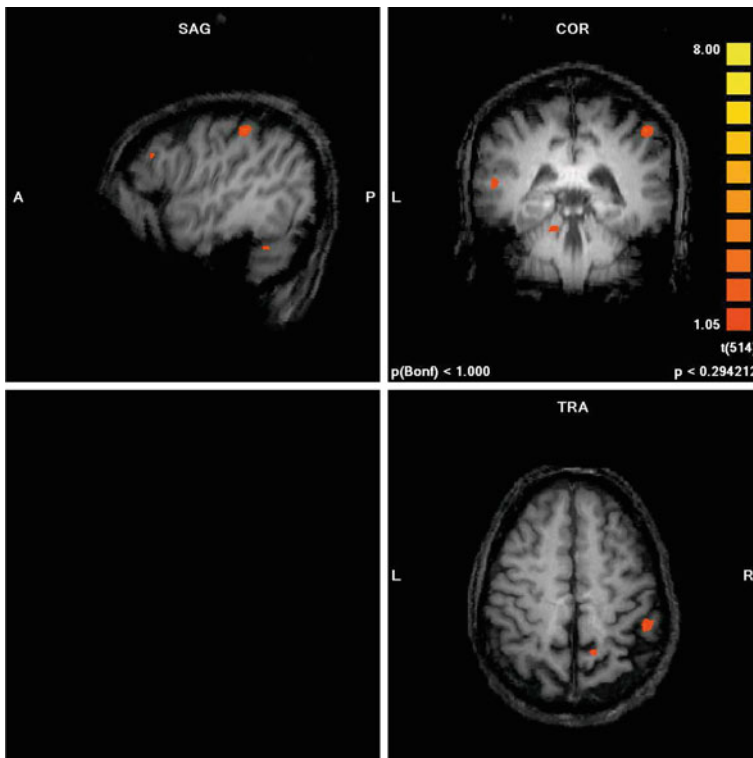


Fig. 7.3 Example of real fMRI activation, the larger activated area is the right anterior intraparietal sulcus (AIP). The views are as follows. *Top-left image* sagittal view (from the *left side* of the head); *top-right image* coronal view (from the *back* of the head); *bottom-right image* transversal view (from the *top* of the head)

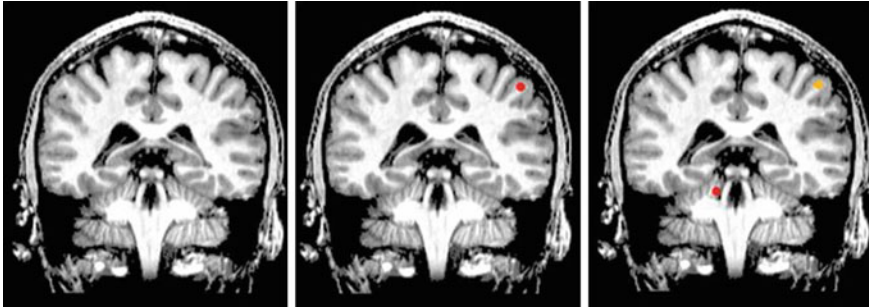


Fig. 7.4 Simulated fRI activation; no activation on the *left*, right AIP activation in the center, right AIP and left cerebellum activations on the *right*

obtained in an fMRI grasping experiment, in which the strongest of the visible activations corresponds to the right AIP. Using a high-resolution anatomical MRI scan as base, and extracting from it the required layers, activations can be superimposed and visualized by color-coding the coordinates corresponding to the areas that are active during the execution of a certain task. Being an area composed of one or more modules, its level of activation depends on the number of modules which are active at a given moment.

In Fig. 7.4 an example of the simulated functional imaging is given: a coronal layer of an anatomical scan is shown on the left with no activations, in the center with a superposed activation in the right AIP area, and on the right with two activations, one again in AIP, but with a lighter color and thus stronger, and another one in the left side of the cerebellum.

The dynamical behavior of the modules during a given task should be such that the pattern of activations is not known beforehand. Only in this way, the visualization of the activity of the “robot brain” allows to make a prediction of how a human model of connectivity would behave in a certain case (i.e. with a given input set). The choices taken during the modeling process will thus reflect in the activation observed in the simulated fMRI environment.

7.3.3 *Reproducing and Predicting Experiments*

The first step for fine-tuning the connectivity methods and test the real value of the tool is to use it for replicating real fMRI experiments. This process starts from a set of modules which supposedly allows for the execution of a number of tasks. An fMRI experiment regarding one such tasks is then chosen from the literature. Different input sets, corresponding to the conditions of the experimental protocol, are defined, and the robot performs the given task with all possible inputs. The behavior of the robot during the experimental session as visualized in the fRI is thus expected to reflect

the activation of the same areas of the brain as in the original fMRI experiment. Of course, only the subset of areas included in the model can be considered: it is not plausible to include all areas normally activated by a given experiment, as this would imply the use of a largely implausible model of the whole brain. The following step would be to predict the outcome of new experiments, using the fRI in conjunction with the appropriate model. An example of how this can be achieved is provided in the next section.

7.3.4 fRI of the Posterior Parietal Cortex

The literature of neuroscience studies on vision-based grasping offers various experiments which can be reproduced with the fRI platform. A very interesting case is the analysis of the different patterns of activation obtained during power and precision grips. So far, no extensive results were available until recent research showed that AIP is much more active during precision grips than for power grips (Begliomini et al. 2007; Cavina-Pratesi et al. 2007). Previously, only Ehrsson et al. (2000) performed this experiment in the dark, observing that precision grips activate AIP more than power grips. Results for CIP are still not available.

The starting point for the test is the mapping of CIP neuronal activation to the fundamental grip taxonomy described in Sect. 7.1. According to the described framework, precision grips should activate either one or both of SOS and AOS neurons, depending on the exact size and shape of the target feature, whilst full-hand power grips would not consistently activate any orientation selective neurons. This would reflect in a higher activation of CIP for precision grips compared to power grips. It is also very plausible that grasp planning in AIP is going to be much more complex for precision than for power grips, as in the latter case no elaborate analysis for finger positioning is necessary, which should reflect in a lower activation. Robot grasping experiments based on the model are thus very likely to show increasing activation in both CIP and AIP for precision compared to power grips. It would be interesting though to observe the modulation in the observed activation according to gradually changing shapes and sizes of the objects. Performing these same grasping experiments on a real fMRI setup with human subjects could provide a comparison for testing the appropriateness of the model.

For illustration purposes, Fig. 7.5 shows the activation pattern expected in this example: left AIP is shown on the left, left CIP on the right. The Talairach coordinates of the areas are those provided by Shikata et al. (2003).

As anticipated above, this pattern of activity has recently been confirmed for AIP, but not yet for CIP, which is anyway a more controversial area in human studies. Future studies could thus assess the problem of more clearly identifying where in the human brain feature extraction is performed. Also, differential activations of AIP in various conditions can provide further cues on how exactly visual information is used for generating grasp configurations according to the model framework.

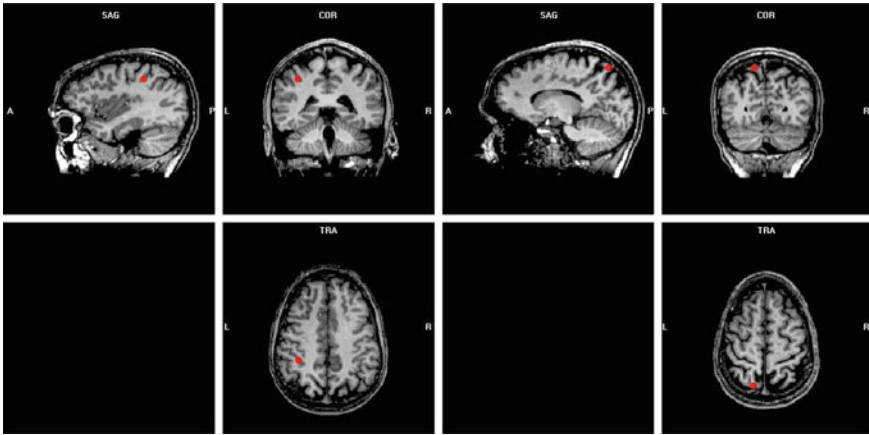


Fig. 7.5 fRI activations of left AIP (*left*) and left CIP (*right*)

7.3.5 The Brain-Damaged Robot

Brain lesions have probably been the best source of information for neuroscientists before the advent of brain imaging techniques. As mentioned in Chap. 2 the two streams theory, was first proposed by Goodale and Milner after observing the singular behavior of *visual agnosia* and *optic ataxia* patients (Goodale and Milner 1992). Reproducing the behavior of such patients can be an interesting test for the model and the fRI interface. This could be done in two complementary ways: modifying the connectivity of models, and introducing different quantities of noise in the data flow. The outcome may be used to determine which patterns of connectivity, when appropriately damaged, would actually generate the behavior observed in impaired humans. Nowadays, only transcranial magnetic stimulation (see text box on TMS) experiments can partially reproduce the effect of local brain lesions, but the tool is controversial as potentially unsafe, and it suffers from low resolution and limited access to a large part of the brain.

Several interesting experiments on brain lesion modeling could be performed. For example, optic ataxia, which is a consequence of dorsal stream damages, should strongly affect the grip generation and execution process, so that grasping actions may fail or being clumsily executed. Different effects would be produced by different connectivity changes, and hypothesis on exactly what parts of the dorsal stream may be affected can be made.

Computational modeling of brain lesions is not a completely new approach (Pouget and Sejnowski 2001; Salinas and Sejnowski 2001), and a model of impaired brain functions in grasping could be applied to a simulated environment. Nevertheless, the uncertainty of the real world can never be properly reproduced with only computational models, and even a simplified embodiment provides a different significance to the experimental validation. Implementation on a robotic setup surely

requires an additional effort, but this is balanced by the more general value of the obtained results.

Summarizing, the proposed modeling approach and the fRI tool for interfacing computational models with robotic experiments aim at facilitating the interplay and the mutual positive influence between the research fields of robotics and neuroscience. The fRI interface can be used as an aid for the design of fMRI experiments and for the validation of functional brain models. Also, it can be used for “impossible experiments”, as local temporary brain damaging, which cannot be performed on human subjects.

7.4 Further Extensions

In the previous sections, fundamental developments to the work presented in the book have been introduced and thoroughly discussed. There are other relevant aspects that have not been included in the current research. A few of them are summarized below.

7.4.1 *Temporal Coordination*

The dynamic aspects of visuomotor transformations and movement coordination have not been thoroughly considered in the current research. All steps from visual acquisition to object lifting are executed sequentially, following the data flow, and in the case of concurrent processes (such as in ventral and dorsal visual analysis), the adopted solution is simply that the faster process waits for the slower.

For what concerns visual cue integration, it seems that binocular cues are processed faster than monocular ones (Greenwald et al. 2005). This can be explained by the fact that interpretation of monocular cues normally requires semantic knowledge and hence some ventral stream processing, whilst stereoptic analysis is performed entirely within the dorsal stream. The consequence is that temporal constraints affect cue integration, and binocular cues are especially dominant during online action control.

Regarding coordination in action execution, it surely involves IPS and PMv, but other areas too. The supplementary motor area (Picard and Strick 2003; Ogawa et al. 2006) and the dorsal premotor cortex (Davare et al. 2006) are almost certainly part of the circuit dedicated to the sequencing of action components in reaching and grasping, but the most important role in action coordination is very likely played by the cerebellum (Doya 1999; Cotterill 2001; Ramnani et al. 2001). More complex mechanisms, and the contribution of other areas, seem to be required when grasping involves moving objects (Schenk et al. 2005; Sakata et al. 1997). An additional aspect that should be taken into account is the coordination between eye and arm movements (Johansson et al. 2001). In a research work largely complementary to that presented in this book, Chinellato et al. (2011) have developed a bio-inspired system

for visuomotor integration based on the contextual learning and the coordinated control of eye gazing and arm reaching movements. This has allowed to produce a robotic system able to create its own internal model and its representation of the surrounding space by interacting with the environment directly, through a mutual adaptation of perception and action (Antonelli et al. 2014).

7.4.2 Tools

Although other primates can successfully learn how to use simple tools, humans are the only species specialized for tool manipulation. Indeed, most of our every-day activities require the handling of purposely manufactured objects. Tool use is thus an extremely revealing aspect for studying the evolution of the human brain as compared to monkeys’.

Familiarity with objects surely affect the way we interact with them (Gentilucci 2003), but tools seem to constitute a completely autonomous class of objects to this regard (Creem-Regehr and Lee 2005; Hoeren et al. 2013). It has been suggested that there are neural mechanisms especially dedicated to tool handling (Johnson-Frey et al. 2005; Orban and Caruana 2014), and that tools at reachable distances seem to constitute a focus of attention more powerful than other graspable objects (Handy et al. 2003). Sugioet al. (2003a) compared the fMRI activation of grasping familiar objects with explicit graspable features, such as handles, and other graspable objects without handles. The latter were found to elicit the usual AIP–PMv circuit, but the former apparently activated learned visuomotor associations at subcortical areas, like the rostral cingulate motor area. The same area is not activated for geometric objects with handle-like parts, implying that the activation is related to semantic meanings rather than to geometric features (Sugio et al. 2003b). According to the authors these results suggest the existence of a “direct” route from vision to action especial for tools, which is essentially affected by semantic and associative factors.

7.4.3 Grasping Force

The grasping literature distinguishes between grip and lift force, suggesting that, although related, they are controlled by parallel processes (Quaney et al. 2005), and that they are both independent from the reaching movement (Biegstraaten et al. 2006). The use of force has been much simplified in the proposed framework, but there are many factors which affects force distribution, and many of them are unpredictable before contact (Baud-Bovy and Soechting 2002). The influence of object weight, expected friction and compliance have already been mentioned, and the control of grasping forces, probably performed by AIP (Ehrsson et al. 2003), takes into account all of them (Gordonet al. 1993). Indeed, complex interactions between the streams seem to underlie the anticipatory scaling and the subsequent monitoring of grasping

forces (Westwood et al. 2000; Reichenbach et al. 2014). Nevertheless, the nature of the contact and the exact situation can be assessed only after touching the object, and two different control strategies for balancing forces and moments seem to be contextually pursued, and the resulting commands summed up (Zatsiorsky et al. 2004). The biggest challenge in modeling force control in grasping is probably the fast adaptation exhibited by subjects in learning the most appropriate force patterns in each condition. Salimi et al. (2000) suggest that this is achieved through the modulation of multiple internal representations, and Ulloa et al. (2003) implemented a plausible model of force learning based on cerebellar mechanisms.

7.4.4 Illusions

Visual and visuomotor illusions constitute interesting tools for studying complex perceptual mechanisms. For what concerns the two streams theory, common illusions have been found not to affect grip scaling as they do with size judgment (Servos et al. 2000). Force scaling seems to be also largely spared by illusions, but several factors such as relative size, delays and environmental conditions all affect the response to illusions (Westwood and Goodale 2003; Handlovsky et al. 2004). Some researchers argue that the observed effects are not due to the dualism between the dorsal and ventral streams (Franz et al. 2001; Dassonville and Bala 2004). Nevertheless, recent studies appositely designed to disambiguate the effect of illusions and solve the controversy, support the perception/action dualism (Kwok and Braddick 2003; Stöttinger and Perner 2006; Plewan et al. 2012).

As for brain damages, the modeling and simulation of illusory effects can be of great interest for the validation of modeling hypotheses on the function and connectivity of visual and visuomotor areas.

Other aspects related to vision based grasping and to the two streams theory that are worth further exploration and modeling efforts are: laterality and the task sharing between the left and right brain hemispheres (Cavina-Pratesi et al. 2006; Culham et al. 2006; Rice et al. 2007; Vainio et al. 2007); the controversial issue of visuomotor priming (Craighero et al. 2002; Cant et al. 2005; Yoon and Humphreys 2007) and the related problem of attention allocation (Craighero et al. 1999; Handy et al. 2003; Lavie 2005).

7.5 Conclusions

Interdisciplinary research involving high technology fields and life sciences is getting nowadays more and more common. Artificial intelligence has been from its very foundation a meeting-place for scientists of seemingly unrelated disciplines. Two such disciplines which met thanks to artificial intelligence are robotics and neuroscience, and although their encounter is producing very interesting developments,

fundamental differences in research goals, methodologies and language prevent a more proficuous collaboration. To this regard, the main achievement of our work is to present in a real unified framework two approaches to the issue of vision-based grasping, neuroscientific and robotic, that are usually completely independent from each other.

References

- Amedi A, Malach R, Hendler T, Peled S, Zohary E (2001) Visuo-haptic object-related activation in the ventral visual pathway. *Nat Neurosci* 4(3):324–330. doi:[10.1038/85201](https://doi.org/10.1038/85201)
- Antonelli M, Gibaldi A, Beuth F, Duran A, Canessa A, Chessa M, Solari F, del Pobil A, Hamker F, Chinellato E, Sabatini S (2014) A hierarchical system for a distributed representation of the peripersonal space of a humanoid robot. *IEEE Trans Auton Mental Dev* 6(4):259–273. doi:[10.1109/TAMD.2014.2332875](https://doi.org/10.1109/TAMD.2014.2332875)
- Arbib MA, Billard A, Iacoboni M, Oztot E (2000) Synthetic brain imaging: grasping, mirror neurons and imitation. *Neural Netw* 13(8–9):975–997
- Baud-Bovy G, Soechting JF (2002) Factors influencing variability in load forces in a tripod grasp. *Exp Brain Res* 143(1):57–66. doi:[10.1007/s00221-001-0966-8](https://doi.org/10.1007/s00221-001-0966-8)
- Begliomini C, Wall MB, Smith AT, Castiello U (2007) Differential cortical activity for precision and whole-hand visually guided grasping in humans. *Eur J Neurosci* 25(4):1245–1252. doi:[10.1111/j.1460-9568.2007.05365.x](https://doi.org/10.1111/j.1460-9568.2007.05365.x)
- Biegstraaten M, Smeets JBJ, Brenner E (2006) The relation between force and movement when grasping an object with a precision grip. *Exp Brain Res* 171(3):347–357. doi:[10.1007/s00221-005-0271-z](https://doi.org/10.1007/s00221-005-0271-z)
- Binkofski F, Buccino G, Zilles K, Fink GR (2004) Supramodal representation of objects and actions in the human inferior temporal and ventral premotor cortex. *Cortex* 40(1):159–161
- Bosco A, Breveglieri R, Chinellato E, Galletti C, Fattori P (2009) Influence of visual feedback on reaching activity in parietal area V6A. In: Annual meeting of the society for neuroscience, 2009
- Cant JS, Westwood DA, Valyear KF, Goodale MA (2005) No evidence for visuomotor priming in a visually guided action task. *Neuropsychologia* 43(2):216–226. doi:[10.1016/j.neuropsychologia.2004.11.008](https://doi.org/10.1016/j.neuropsychologia.2004.11.008)
- Cavina-Pratesi C, Monaco S, McAdam T, Milner D, Schenk T, Culham JC (2007) Which aspects of hand-preshaping does human AIP compute during visually guided actions? Evidence from event-related fMRI. In: Annual meeting of the society for neuroscience
- Cavina-Pratesi C, Valyear KF, Culham JC, Köhler S, Obhi SS, Marzi CA, Goodale MA (2006) Dissociating arbitrary stimulus-response mapping from movement planning during preparatory period: evidence from event-related functional magnetic resonance imaging. *J Neurosci* 26(10):2704–2713. doi:[10.1523/JNEUROSCI.3176-05.2006](https://doi.org/10.1523/JNEUROSCI.3176-05.2006)
- Chinellato E, Antonelli M, Grzyb B, del Pobil A (2011) Implicit sensorimotor mapping of the peripersonal space by gazing and reaching. *IEEE Trans Autonom Mental Dev* 3(1):43–53. doi:[10.1109/TAMD.2011.2106781](https://doi.org/10.1109/TAMD.2011.2106781)
- Chinellato E, del Pobil AP (2008) fRI, functional robotic imaging: Visualizing a robot brain. In: IEEE international conference on distributed human-machine systems
- Chinellato E, Grzyb BJ, Marzocchi N, Bosco A, Fattori P, del Pobil AP (2010) The dorso-medial visual stream: from neural activation to sensorimotor interaction. *Neurocomputing* (In Press). doi:[10.1016/j.neucom.2010.07.029](https://doi.org/10.1016/j.neucom.2010.07.029)
- Cloutman LL (2013) Interaction between dorsal and ventral processing streams: where, when and how? *Brain Lang* 127(2):251–263. doi:[10.1016/j.bandl.2012.08.003](https://doi.org/10.1016/j.bandl.2012.08.003)

- Cotterill RM (2001) Cooperation of the basal ganglia, cerebellum, sensory cerebrum and hippocampus: possible implications for cognition, consciousness, intelligence and creativity. *Prog Neurobiol* 64(1):1–33
- Craigero L, Fadiga L, Rizzolatti G, Umiltà C (1999) Action for perception: a motor-visual attentional effect. *J Exp Psychol Hum Percept Perform* 25(6):1673–1692
- Craigero L, Bello A, Fadiga L, Rizzolatti G (2002) Hand action preparation influences the responses to hand pictures. *Neuropsychologia* 40(5):492–502
- Creem-Regehr SH, Lee JN (2005) Neural representations of graspable objects: are tools special? *Cogn Brain Res* 22(3):457–469. doi:[10.1016/j.cogbrainres.2004.10.006](https://doi.org/10.1016/j.cogbrainres.2004.10.006)
- Culham JC, Cavina-Pratesi C, Singhal A (2006) The role of parietal cortex in visuomotor control: what have we learned from neuroimaging? *Neuropsychologia* 44(13):2668–2684. doi:[10.1016/j.neuropsychologia.2005.11.003](https://doi.org/10.1016/j.neuropsychologia.2005.11.003)
- Culham JC (2006) Functional neuroimaging: experimental design and analysis. In: Cabeza R, Kingstone A (eds) *Handbook of functional neuroimaging of cognition*. MIT Press, Cambridge, pp 53–82
- Dassonville P, Bala JK (2004) Perception, action, and Roelofs effect: a mere illusion of dissociation. *PLoS Biol* 2(11):e364. doi:[10.1371/journal.pbio.0020364](https://doi.org/10.1371/journal.pbio.0020364)
- Davare M, Andres M, Cosnard G, Thonnard JL, Olivier E (2006) Dissociating the role of ventral and dorsal premotor cortex in precision grasping. *J Neurosci* 26(8):2260–2268. doi:[10.1523/JNEUROSCI.3386-05.2006](https://doi.org/10.1523/JNEUROSCI.3386-05.2006)
- Dearden AM, Demiris Y (2005) Learning forward models for robots. In: *International joint conferences on artificial intelligence*, pp 1440–1445
- Doya K (1999) What are the computations of the cerebellum, the basal ganglia and the cerebral cortex? *Neural Netw* 12(7–8):961–974
- Ehrsson HH, Fagergren A, Johansson RS, Forssberg H (2003) Evidence for the involvement of the posterior parietal cortex in coordination of fingertip forces for grasp stability in manipulation. *J Neurophysiol* 90(5):2978–2986. doi:[10.1152/jn.00958.2002](https://doi.org/10.1152/jn.00958.2002)
- Ehrsson HH, Fagergren A, Jonsson T, Westling G, Johansson RS, Forssberg H (2000) Cortical activity in precision- versus power-grip tasks: an fMRI study. *J Neurophysiol* 83(1):528–536
- Ernst MO, Banks MS, Bühlhoff HH (2000) Touch can change visual slant perception. *Nat Neurosci* 3(1):69–73. doi:[10.1038/71140](https://doi.org/10.1038/71140)
- Fattori P, Raos V, Breviglieri R, Bosco A, Marzocchi N, Galletti C (2010) The dorsomedial pathway is not just for reaching: grasping neurons in the medial parieto-occipital cortex of the macaque monkey. *J Neurosci* 30(1):342–3490. <http://dx.doi.org/0>
- Franz VH, Fahle M, Bühlhoff HH, Gegenfurtner KR (2001) Effects of visual illusions on grasping. *J Exp Psychol Hum Percept Perform* 27(5):1124–1144
- Frey SH, Vinton D, Norlund R, Grafton ST (2005) Cortical topography of human anterior intraparietal cortex active during visually guided grasping. *Cogn Brain Res* 23(2–3):397–405. doi:[10.1016/j.cogbrainres.2004.11.010](https://doi.org/10.1016/j.cogbrainres.2004.11.010)
- Fukuda H, Fukumura N, Katayama M, Uno Y (2000) Relation between object recognition and formation of hand shape: a computational approach to human grasping movements. *Syst Comput Jpn* 31(12):11–22
- Gentilucci M (2003) Object familiarity affects finger shaping during grasping of fruit stalks. *Exp Brain Res* 149(3):395–400. doi:[10.1007/s00221-003-1370-3](https://doi.org/10.1007/s00221-003-1370-3)
- Goodale MA (2008) Action without perception in human vision. *Cogn Neuropsychol* 25(7–8):891–919. doi:[10.1080/02643290801961984](https://doi.org/10.1080/02643290801961984)
- Goodale MA, Milner AD (1992) Separate visual pathways for perception and action. *Trends Neurosci* 15(1):20–25
- Gordon AM, Westling G, Cole KJ, Johansson RS (1993) Memory representations underlying motor commands used during manipulation of common and novel objects. *J Neurophysiol* 69(6):1789–1796
- Greenwald HS, Knill DC, Saunders JA (2005) Integrating visual cues for motor control: a matter of time. *Vis Res* 45(15):1975–1989. doi:[10.1016/j.visres.2005.01.025](https://doi.org/10.1016/j.visres.2005.01.025)

- Handlovsky I, Hansen S, Lee TD, Elliott D (2004) The Ebbinghaus illusion affects on-line movement control. *Neurosci Lett* 366(3):308–311. doi:[10.1016/j.neulet.2004.05.056](https://doi.org/10.1016/j.neulet.2004.05.056)
- Handy TC, Grafton ST, Shroff NM, Ketay S, Gazzaniga MS (2003) Graspable objects grab attention when the potential for action is recognized. *Nat Neurosci* 6(4):421–427, 431
- Hoeren M, Kaller CP, Glauche V, Vry MS, Rijntjes M, Hamzei F, Weiller C (2013) Action semantics and movement characteristics engage distinct processing streams during the observation of tool use. *Exp Brain Res* 229(2):243–260. doi:[10.1007/s00221-013-3610-5](https://doi.org/10.1007/s00221-013-3610-5)
- Hu Y, Osu R, Okada M, Goodale MA, Kawato M (2005) A model of the coupling between grip aperture and hand transport during human prehension. *Exp Brain Res* 167(2):301–304. doi:[10.1007/s00221-005-0111-1](https://doi.org/10.1007/s00221-005-0111-1)
- Jeannerod M (1999) Visuomotor channels: their integration in goal-directed prehension. *Hum Mov Sci* 18(2):201–218. doi:[10.1016/S0167-9457\(99\)00008-1](https://doi.org/10.1016/S0167-9457(99)00008-1)
- Jiang J, Shen Y, Neilson PD (2002) A simulation study of the degrees of freedom of movement in reaching and grasping. *Hum Mov Sci* 21(5–6):881–904
- Johansson RS, Westling G, Bäckström A, Flanagan JR (2001) Eye-hand coordination in object manipulation. *J Neurosci* 21(17):6917–6932
- Johnson-Frey SH, Newman-Norlund R, Grafton ST (2005) A distributed left hemisphere network active during planning of everyday tool use skills. *Cerebral Cortex* 15(6):681–695. doi:[10.1093/cercor/bhh169](https://doi.org/10.1093/cercor/bhh169)
- Kawato M (1999) Internal models for motor control and trajectory planning. *Curr Opin Neurobiol* 9:718–727
- Kwok RM, Braddick OJ (2003) When does the Titchener Circles illusion exert an effect on grasping? Two- and three-dimensional targets. *Neuropsychologia* 41(8):932–940
- Lavie N (2005) Distracted and confused?: selective attention under load. *Trends Cogn Sci* 9(2):75–82. doi:[10.1016/j.tics.2004.12.004](https://doi.org/10.1016/j.tics.2004.12.004)
- Lim B, Ra S, Park F (2005) Movement primitives, principal component analysis, and the efficient generation of natural motions. In: *IEEE international conference on robotics and automation*, pp 4630–4635
- Loftus A, Servos P, Goodale MA, Mendarozqueta N, Mon-Williams M (2004) When two eyes are better than one in prehension: monocular viewing and end-point variance. *Exp Brain Res* 158(3):317–327. doi:[10.1007/s00221-004-1905-2](https://doi.org/10.1007/s00221-004-1905-2)
- Metzinger T, Gallese V (2003) The emergence of a shared action ontology: building blocks for a theory. *Conscious Cogn* 12(4):549–571
- Miall R (2003) Connecting mirror neurons and forward models. *Neuroreport* 14(16):1–3
- Mon-Williams M, Tresilian JR (1999) Some recent studies on the extraretinal contribution to distance perception. *Perception* 28(2):167–181
- Mon-Williams M, Tresilian JR (2001) A simple rule of thumb for elegant prehension. *Curr Biol* 11(13):1058–1061
- Murata A, Gallese V, Luppino G, Kaseda M, Sakata H (2000) Selectivity for the shape, size, and orientation of objects for grasping in neurons of monkey parietal area AIP. *J Neurophysiol* 83(5):2580–2601
- Nori F, Frezza R (2005) Control of a manipulator with a minimum number of motion primitives. In: *IEEE international conference on robotics and automation*, pp 2344–2349
- Ogawa K, Inui T, Sugio T (2006) Separating brain regions involved in internally guided and visual feedback control of moving effectors: an event-related fMRI study. *Neuroimage* 32(4):1760–1770. doi:[10.1016/j.neuroimage.2006.05.012](https://doi.org/10.1016/j.neuroimage.2006.05.012)
- Orban GA, Caruana F (2014) The neural basis of human tool use. *Front Psychol* 5:310. doi:[10.3389/fpsyg.2014.00310](https://doi.org/10.3389/fpsyg.2014.00310)
- Perry CJ, Tahiri A, Fallah M (2014) Feature integration within and across visual streams occurs at different visual processing stages. *J Vis* 14(2). doi:[10.1167/14.2.10](https://doi.org/10.1167/14.2.10)
- Picard N, Strick PL (2003) Activation of the supplementary motor area (SMA) during performance of visually guided movements. *Cereb Cortex* 13(9):977–986

- Plewan T, Weidner R, Eickhoff SB, Fink GR (2012) Ventral and dorsal stream interactions during the perception of the müller-lyer illusion: evidence derived from fmri and dynamic causal modeling. *J Cogn Neurosci* 24(10):2015–2029
- Pouget A, Sejnowski TJ (2001) Simulating a lesion in a basis function model of spatial representations: comparison with hemineglect. *Psychol Rev* 108(3):653–673
- Quaney BM, Nudo RJ, Cole KJ (2005) Can internal models of objects be utilized for different prehension tasks? *J Neurophysiol* 93(4):2021–2027. doi:[10.1152/jn.00599.2004](https://doi.org/10.1152/jn.00599.2004)
- Ramrani N, Toni I, Passingham RE, Haggard P (2001) The cerebellum and parietal cortex play a specific role in coordination: a PET study. *Neuroimage* 14(4):899–911. doi:[10.1006/nimg.2001.0885](https://doi.org/10.1006/nimg.2001.0885)
- Reichenbach A, Thielscher A, Peer A, Bühlhoff HH, Bresciani JP (2014) A key region in the human parietal cortex for processing proprioceptive hand feedback during reaching movements. *Neuroimage* 84:615–625. doi:[10.1016/j.neuroimage.2013.09.024](https://doi.org/10.1016/j.neuroimage.2013.09.024)
- Rice NJ, Tunik E, Cross ES, Grafton ST (2007) On-line grasp control is mediated by the contralateral hemisphere. *Brain Res* 1175:76–84. doi:[10.1016/j.brainres.2007.08.009](https://doi.org/10.1016/j.brainres.2007.08.009)
- Rizzolatti G, Luppino G (2001) The cortical motor system. *Neuron* 31(6):889–901
- Roy A, Paulignan Y, Meunier M, Boussaoud D (2002) Prehension movements in the macaque monkey: Effects of object size and location. *Mach Learn* 88(3):1491–1499
- Sakata H, Taira M, Kusunoki M, Murata A, Tanaka Y (1997) The TINS lecture. The parietal association cortex in depth perception and visual control of hand action. *Trends Neurosci* 20(8):350–357
- Salimi I, Hollender I, Frazier W, Gordon AM (2000) Specificity of internal representations underlying grasping. *J Neurophysiol* 84(5):2390–2397
- Salinas E, Sejnowski TJ (2001) Gain modulation in the central nervous system: where behavior, neurophysiology, and computation meet. *Neuroscientist* 7(5):430–440
- Schenk T, Ellison A, Rice N, Milner AD (2005) The role of V5/MT+ in the control of catching movements: an rTMS study. *Neuropsychologia* 43(2):189–198. doi:[10.1016/j.neuropsychologia.2004.11.006](https://doi.org/10.1016/j.neuropsychologia.2004.11.006)
- Servos P, Carnahan H, Fedwick J (2000) The visuomotor system resists the horizontal-vertical illusion. *J Mot Behav* 32(4):400–404
- Shadmehr R, Wise SP (2005) *The computational neurobiology of reaching and pointing: a foundation for motor learning*. MIT Press, Cambridge
- Shikata E, Hamzei F, Glauche V, Koch M, Weiller C, Binkofski F, Büchel C (2003) Functional properties and interaction of the anterior and posterior intraparietal areas in humans. *Eur J Neurosci* 17(5):1105–1110
- Shmuelof L, Zohary E (2005) Dissociation between ventral and dorsal fMRI activation during object and action recognition. *Neuron* 47(3):457–470. doi:[10.1016/j.neuron.2005.06.034](https://doi.org/10.1016/j.neuron.2005.06.034)
- Smeets JBJ, Brenner E, Biegstraaten M (2002) Independent control of the digits predicts an apparent hierarchy of visuomotor channels in grasping. *Behav Brain Res* 136(2):427–432
- Stöttinger E, Perner J (2006) Dissociating size representation for action and for conscious judgment: Grasping visual illusions without apparent obstacles. *Conscious Cogn* 15(2):269–284. doi:[10.1016/j.concog.2005.07.004](https://doi.org/10.1016/j.concog.2005.07.004)
- Sugio T, Inui T, Matsuo K, Matsuzawa M, Glover GH, Nakai T (1999) The role of the posterior parietal cortex in human object recognition: a functional magnetic resonance imaging study. *Neurosci Lett* 276(1):45–48
- Sugio T, Ogawa K, Inui T (2003a) Multiple action representations of familiar objects with handles: an fMRI study. In: *European conference on visual perception*
- Sugio T, Ogawa K, Inui T (2003b) Neural correlates of semantic effects on grasping familiar objects. *Neuroreport* 14(18):2297–2301. doi:[10.1097/01.wnr.0000092474.09492.3a](https://doi.org/10.1097/01.wnr.0000092474.09492.3a)
- Talairach J, Tournoux P (1988) *Co-planar stereotaxic atlas of the human brain*. Thieme, Stuttgart
- Tankus A, Fried I (2012) Visuomotor coordination and motor representation by human temporal lobe neurons. *J Cogn Neurosci* 24(3):600–610

- Tanné-Gariépy J, Rouiller EM, Boussaoud D (2002) Parietal inputs to dorsal versus ventral premotor areas in the macaque monkey: evidence for largely segregated visuomotor pathways. *Exp Brain Res* 145(1):91–103. doi:[10.1007/s00221-002-1078-9](https://doi.org/10.1007/s00221-002-1078-9)
- Ulloa A, Bullock D (2003) A neural network simulating human reach-grasp coordination by continuous updating of vector positioning commands. *Neural Netw* 16(8):1141–1160. doi:[10.1016/S0893-6080\(03\)00079-0](https://doi.org/10.1016/S0893-6080(03)00079-0)
- Ulloa A, Bullock D, Rhodes BJ (2003) Adaptive force generation for precision-grip lifting by a spectral timing model of the cerebellum. *Neural Netw* 16(5–6):521–528. doi:[10.1016/S0893-6080\(03\)00094-7](https://doi.org/10.1016/S0893-6080(03)00094-7)
- Vainio L, Ellis R, Tucker M, Symes E (2007) Local and global affordances and manual planning. *Exp Brain Res* 179(4):583–594. doi:[10.1007/s00221-006-0813-z](https://doi.org/10.1007/s00221-006-0813-z)
- Valyear KF, Cavinaspatesi C, Stiglick AJ, Culham JC (2007) Does tool-related fMRI activity within the intraparietal sulcus reflect the plan to grasp? *Neuroimage* 36(Suppl 2):T94–T108. doi:[10.1016/j.neuroimage.2007.03.031](https://doi.org/10.1016/j.neuroimage.2007.03.031)
- van de Kamp C, Zaal FTJM (2007) Prehension is really reaching and grasping. *Exp Brain Res* 182(1):27–34. doi:[10.1007/s00221-007-0968-2](https://doi.org/10.1007/s00221-007-0968-2)
- Verhoef BE, Vogels R, Janssen P (2011) Synchronization between the end stages of the dorsal and the ventral visual stream. *J Neurophysiol* 105(5):2030–2042. doi:[10.1152/jn.00924.2010](https://doi.org/10.1152/jn.00924.2010)
- Westwood DA, Dubrowski A, Carnahan H, Roy EA (2000) The effect of illusory size on force production when grasping objects. *Exp Brain Res* 135(4):535–543
- Westwood DA, Goodale MA (2003) Perceptual illusion and the real-time control of action. *Spat Vis* 16(3–4):243–254
- Wokke ME, Scholte HS, Lamme VAF (2014) Opposing dorsal/ventral stream dynamics during figure-ground segregation. *J Cogn Neurosci* 26(2):365–379
- Wolpert DM, Ghahramani Z (2000) Computational principles of movement neuroscience. *Nat Neurosci* 3(Suppl):1212–1217. doi:[10.1038/81497](https://doi.org/10.1038/81497)
- Yoon EY, Humphreys GW (2007) Dissociative effects of viewpoint and semantic priming on action and semantic decisions: evidence for dual routes to action from vision. *Q J Exp Psychol: Colchester* 60(4):601–623. doi:[10.1080/17470210600701007](https://doi.org/10.1080/17470210600701007)
- Zanon M, Busan P, Monti F, Pizzoloto G, Battaglini PP (2010) Cortical connections between dorsal and ventral visual streams in humans: evidence by tms/eeG co-registration. *Brain Topogr* 22(4):307–317. doi:[10.1007/s10548-009-0103-8](https://doi.org/10.1007/s10548-009-0103-8)
- Zatsiorsky VM, Latash ML, Gao F, Shim JK (2004) The principle of superposition in human prehension. *Robotica* 22(2):231–234. doi:[10.1017/S0263574703005344](https://doi.org/10.1017/S0263574703005344)