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CHAPTER 4

Apraxia: a review

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Abstract: Praxic functions are frequently altered following brain lesion, giving rise to apraxia — a complex pattern of impairments that is difficult to assess or interpret. In this chapter, we review the current taxonomies of apraxia and related cognitive and neuropsychological models. We also address the questions of the neuroanatomical correlates of apraxia, the relation between apraxia and aphasia and the analysis of apraxic errors. We provide a possible explanation for the difficulties encountered in investigating apraxia and also several approaches to overcome them, such as systematic investigation and modeling studies. Finally, we argue for a multidisciplinary approach. For example, apraxia should be studied in consideration with and could contribute to other fields such as normal motor control, neuroimaging and neurophysiology.

Keywords: apraxia; brain lesion; neuropsychological models of apraxia; kinematic studies; computational neuroscience; multidisciplinary approach

Introduction

Apraxia is generally defined as "a disorder of skilled movement not caused by weakness, akinesia, deafferentation, abnormal tone or posture, movement disorders such as tremor or chorea, intellectual deterioration, poor comprehension, or uncooperativeness" (Heilman and Rothi, 1993). Apraxia is thus negatively defined, in terms of what it is not, as a higher order disorder of movement that is *not* due to elementary sensory and/or motor deficits. This definition implies that there are situations where the effector is moved with normal skill (Hermsdörfer et al., 1996). Puzzling parts of apraxia are the *voluntary-automatic dissociation* and *context-dependence*. On the one hand, apraxic patients may spontaneously perform gestures that they cannot perform on command (Schnider et al., 1997). This voluntary-automatic dissociation can be illustrated by an apraxic patient who could use his left hand to shave and comb himself, but could not execute a specific motor action such as opening the hand so as to let go of an object (Lausberg et al., 1999). In this particular case, focusing on the target of the movement rather than on the movement itself increased his chances of a successful execution. On the other hand, the execution of the movement depends heavily on the context of testing (De Renzi et al., 1982). It may be well preserved in a natural context, with a deficit that appears in the clinical setting only, where the patient has to explicitly represent the content of the action outside of the situational props (Jeannerod and Decety, 1995; Leiguarda and Marsden, 2000).

Several authors agree that although apraxia is easy to demonstrate, it has proven difficult to understand. Research on apraxia is filled with

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confusing terminology, contradictory results and doubts that need to be resolved (De Renzi et al., 1982; Goldenberg et al., 1996; Graham et al., 1999; Koski et al., 2002; Laeng, 2006). Inconsistencies between similar studies may be explained by differences in the methodological and statistical approaches for the apraxia assessment (i.e., types of gestures used and scoring criteria), chronicity and aetiology of damage and brain lesion localization tools (Haaland et al., 2000). Therefore, it still stands that our understanding of the neural and cognitive systems underlying human praxis is not well established.

The chapter is structured as follows. We first review existing types of apraxia as well as important current and historical models of the apraxic deficit. We then consider the inter- and intra-hemispheric lesion correlates of apraxia. Two other sections are dedicated to the relationship between praxis and language and to the analysis of apraxic errors. We finally discuss the current state-of-the-art in apraxia, and argue for a multidisciplinary approach that encompasses evidence from various fields such as neuroimaging or neurophysiology.

Types of apraxia

This section reviews the current taxonomies of apraxia. Some of the frequently observed types of apraxia have inspired the apraxia models described in the following section, others still challenge them.

Ideational apraxia was historically defined as a disturbance in the conceptual organization of actions. It was first assessed by performing purposive sequences of actions that require the use of various objects in the correct order (e.g., preparing a cup of coffee) (Poeck, 1983). It was later accepted that ideational apraxia is not necessarily associated to complex actions, but is a larger deficit that also concerns the evocation of single actions. In this view, complex sequences of multiple objects are simply more suitable to reveal the deficit, possibly because of the heavier load placed on memory and attentional resources (De Renzi and Lucchelli, 1988). Nonetheless, the term *conceptual apraxia* was introduced to designate content errors in single actions, excluding sequence errors in multi-staged actions with tools[1] (Ochipa et al., 1992; Heilman et al., 1997). In theoretical models, ideational and conceptual apraxia correspond to a disruption of the conceptual component of the praxis system, i.e., action semantics memory, described in more detail in the "Models of apraxia" section (De Renzi and Lucchelli, 1988; Graham et al., 1999). Patients with ideational apraxia are not impaired in the action execution *per se*, but demonstrate inappropriate use of objects and may fail in gesture discrimination and matching tasks. For example, a patient was reported to eat with a toothbrush and brush his teeth with a spoon and a comb. His inability to use tools could not be explained by a motor production deficit that would characterize ideomotor apraxia (defined below). Interestingly, although he was able to name the tools and point to them on command, he could not match the tools with the objects, hence suggesting a loss of knowledge related to the use of tools.

Ideomotor apraxia is considered to be a disorder of the production component of the praxis system, i.e., sensorimotor action programs that are concerned with the generation and control of motor activity (Rapcsak et al., 1995; Graham et al., 1999). It is characterized by errors in the timing, sequencing and spatial organization of gestural movements (Leiguarda, 2001). Since the conceptual part of the praxis system is assumed to be intact, patients with ideomotor apraxia should not use objects and tools in a conceptually inappropriate fashion and should not have difficulty with the serial organization of an action (De Renzi et al., 1982). Ideational and ideomotor apraxia have been assessed by testing the execution of various types of gestures: transitive and intransitive (i.e., with or without the use of tools or objects), meaningless non-representational (e.g., hand postures relative to head) and meaningful representational (e.g., waving good-bye), complex sequences with multiple objects, repetitive movements, distal and proximal gestures (e.g., imitation of finger and hand configurations), reaching in peri-personal and body-centered space (e.g., targets in near space or on the patient's body), novel movements (i.e., skill acquisition) or imagined

[1]Conceptual apraxia is often observed in Alzheimer's disease.

movements. These gestures can also be executed under different modalities such as: verbal command, imitation, pantomime and tactile or visual presentation of objects.

The use of various gestures and different modalities to assess apraxia has helped to uncover many interesting *functional dissociations* that are listed below. For example, apraxia was shown to be modality-specific, i.e., the same type of gesture was differentially impaired according to the modality of testing (De Renzi et al., 1982). One dissociation, named *conduction apraxia*, is the syndrome of superior performance on verbal command than on imitation (Ochipa et al., 1994). The opposite pattern has also been observed: very poor performance on verbal command that improved on imitation or when seeing the object (Heilman, 1973; Merians et al., 1997). The extreme occurrence of conduction apraxia, namely the selective inability to imitate with normal performance on verbal command was termed *visuo-imitative apraxia* (Merians et al., 1997). In some cases of visuo-imitative apraxia, defective imitation of meaningless gestures (e.g., fist under chin) contrasts with preserved imitation of meaningful gestures (e.g., hitchhiking) (Goldenberg and Hagmann, 1997; Salter et al., 2004). A surprising case of double dissociation from this kind of visuo-imitative apraxia was described in Bartolo et al. (2001), where the patient showed impairment in meaningful gesture production (both on imitation and verbal command) and normal performance in imitation of meaningless gestures, suggesting that the patient was able to reproduce only movements he did not identify or recognize as familiar. Similarly, the apraxic patients in Buxbaum et al. (2003) responded abnormally to familiar objects (e.g., a key, a hammer or a pen) but normally in recognizing the hand postures appropriate for novel objects (e.g., parallelepipeds differing in size and depth). These two studies argue that the reproduction of a gesture may be constrained by its degree of familiarity, indicating that current models of apraxia would need some refinement.

Furthermore, the representation of transitive and intransitive actions may be dissociable. In Watson et al. (1986), bilateral apraxia was observed only for transitive (e.g., hammering) but not intransitive (e.g., hitchhiking, waving goodbye) movements.[2] Whereas transitive gestures are constrained by the shape, size and function of objects, intransitive actions are related to socio-cultural contexts (Cubelli et al., 2000; Heath et al., 2001). The isolated disturbance of transitive hand movements for use of, recognition and interaction with an object, in the presence of preserved intransitive movements, was named tactile apraxia and usually appears in the hand contralateral to the lesion (Binkofski et al., 2001).

As mentioned in the ''Introduction'', contextual cues strongly influence the execution of actions. Some studies have systematically manipulated the contextual cues in order to assess their relative importance. For example, patients with impaired pantomime of motor actions showed no deficit in the comprehension of the use of tools or in manipulating the tools (Halsband et al., 2001). Graham et al. (1999) also observed dramatic facilitation in the demonstration of tool use when the patient was given the appropriate or a neutral tool to manipulate.[3] Interestingly, the patient could not prevent himself from performing the action appropriate to the tool he was holding, rather than the requested action. In another study however, gesture execution improved when the object of the action, but not the tool, was given (Clark et al., 1994). Hence, the addition of visual and somaesthetic cues may improve certain aspects of apraxic movements, since it provides mechanical constraints and supplementary information that facilitates the selection of an adequate motor program (Hermsdörfer et al., 2006). Nonetheless, there is the case of a patient that performed much worse when he was actually manipulating the tool than on verbal command[4] (Merians et al., 1999).

Dissociations that concern the nature of the target were also observed. For example, the left brain damaged patients in Hermsdörfer et al. (2003) had prolonged movement times and reduced maximum velocities when the movements were directed

[2]These patients had lesions in the left supplementary motor area (SMA).

[3]The subject had clinically diagnosed corticobasal degeneration.

[4]Ibid.

toward an allocentric target without visual feedback, but performed normally when the target was their own nose. Also, a clear dissociation was found in Ietswaart et al. (2006) between impaired gesture imitation and intact motor programming of goal-directed movements, hence arguing against the interpretation of impaired imitation as a purely executional deficit (see "Models of apraxia").

A particular type of apraxia is *constructional apraxia*, originally described by Kleist as "the inability to do a construction" and defined by Benton as "the impairment in combinatory or organizing activity in which details must be clearly perceived and in which the relationship among the component parts of the entity must be apprehended" (Laeng, 2006). Constructional apraxic patients are unable to spontaneously draw objects, copy figures and build blocks or patterns with sticks, following damage not only to the dominant but also non-dominant hemisphere. Hence, constructional apraxia appears to reflect the loss of bilaterally distributed components for constructive planning and the perceptual processing of categorical and coordinate spatial relations (Platz and Mauritz, 1995; Laeng, 2006).

Apraxia can also be observed in *mental motor imagery tasks*. Motor imagery is considered as a means of accessing the mechanisms of action preparation and imitation, by sharing a common neural basis (Jeannerod and Decety, 1995). Apraxic patients were deficient in simulating hand actions mentally and in imagining the temporal properties of movements[5] (Sirigu et al., 1999). Other apraxic patients showed a deficit in generating and maintaining internal models for planning object-related actions (Buxbaum et al., 2005a). These findings support the notion that the motor impairments observed in apraxic patients result from a specific alteration in their ability to mentally evoke actions, or to use stored motor representations for forming mental images of actions.

Apraxia may also be appropriate to reveal the role of *feedback* during the execution of a movement. Some apraxic patients were impaired in reaching and aiming movements only in the condition without visual feedback (Ietswaart et al., 2001, 2006) and performed worse during pointing with closed eyes (Jacobs et al., 1999; Hermsdörfer et al., 2003). Interestingly, the patients in Haaland et al. (1999) overshot the target when feedback of the hand was removed and undershot the target when the feedback of the target was unavailable. Importantly, these patients continued to rely on visual feedback during the secondary adjustment phase of the movement and never achieved normal end-point accuracy when visual feedback of the hand position or target location was unavailable. These findings also suggest that ideomotor limb apraxia may be associated with the disruption of the neural representations for the extra-personal (spatial location) and intra-personal (hand position) features of movement (Haaland et al., 1999).

The importance of feedback signals was demonstrated in one of our own apraxic patients (unpublished data). We reproduced a seminal study of imitation of meaningless gestures[6] by Goldenberg et al. (2001) on an apraxic patient with left-parietal ischemic lesion. We observed that the patient relied heavily on visual and tactile feedback. He often needed to bring his hand in the field of vision and corrected the hand posture by directly comparing it with the displayed stimulus to imitate. He also used tactile exploration when searching for the correct spatial position on his face. He showed many hesitations and extensive searching which led to highly disturbed kinematic profiles of the gesture (shown in Fig. 3c, d), but often correct final postures.

Apraxia can also be defined in relation to the selectively affected effectors: *orofacial apraxia* or *buccofacial apraxia, oral apraxia, upper and lower face apraxia, lid apraxia, limb apraxia, leg apraxia, trunk apraxia, etc*. Oral apraxia, for example, is defined as the inability to perform mouth actions such as sucking from a straw or blowing a kiss. It should not be confounded with *apraxia of speech* (also called *verbal apraxia*), which is a selective disturbance of the articulation of words (Bizzozero et al., 2000). Motor planning disorders in children are denominated *developmental dyspraxia* (Cermak, 1985). Apraxia can also designate a praxic ability impaired in an isolated manner such as: *gait*

[5]These patients had posterior parietal lesions.

[6]Hand postures relative to the head, an example is shown in Fig. 3a.

apraxia, apraxic agraphia, dressing apraxia, orienting apraxia and *mirror apraxia* (i.e., inability to reach to objects in a mirror (Binkofski et al., 2003)). When the side of brain lesion and affected hand are considered, the terms *sympathetic* and *crossed apraxia* are used. Apraxia can sometimes be related to the specific neural substrate that causes the disorder, for example following subcortical lesions in corticobasal degeneration (Pramstaller and Marsden, 1996; Jacobs et al., 1999; Merians et al., 1999; Hanna-Pladdy et al., 2001; Leiguarda, 2001) or following lesions of the corpus callosum (Watson and Heilman, 1983; Lausberg et al., 1999, 2000; Goldenberg et al., 2001; Lausberg and Cruz, 2004). *Callosal apraxia* for example is particularly appropriate for disentangling the specific hemispheric contributions to praxis.

An extensive list of the types of apraxia and their definitions, including types that were not mentioned above, can be found in Table 1.

Models of apraxia

Contemporary neuropsychological views of apraxia arise from Liepmann's influential work that dates from more than a hundred years ago. Liepmann proposed the existence of an idea of the movement, "movement formulae", that contains the "time-space-form picture" of the action (Rothi et al., 1991). He believed that in right-handers, these movement formulae are stored in the left-parietal lobe, endorsing the view of a left hemispheric dominance for praxis (Faglioni and Basso, 1985; Leiguarda and Marsden, 2000). To execute a movement, the spatiotemporal image of the movement is transformed into "innervatory patterns" that yield "positioning of the limbs according to directional ideas" (Jacobs et al., 1999). Liepmann distinguished between three types of apraxia that correspond to disruptions of specific components of his model (Faglioni and Basso, 1985; Goldenberg, 2003). First, a damaged movement formula (i.e., faulty integration of the elements of an action) would characterize "ideational apraxia". Second, failure of the transition from the movement formula to motor innervation (i.e., inability to translate a correct idea of the movement into a correct act) is defined as "ideomotor apraxia". According to Liepmann, faulty imitation of movements is a purely executional deficit and proves the separation between the idea and execution of a movement, since in imitation the movement formula is defined by the demonstration (Goldenberg, 1995, 2003; Goldenberg and Hagmann, 1997). Finally, loss of purely kinematic (kinaesthetic or innervatory) inherent memories of an extremity is the "limb-kinetic" variant of apraxia.

Another historically influential model is the disconnection model of apraxia proposed by Geschwind (1965). According to this model the verbal command for the movement is comprehended in Wernicke's area and is transferred to the ipsilateral motor and premotor areas that control the movement of the right hand (Clark et al., 1994; Leiguarda and Marsden, 2000). For a left-hand movement, the information needs to be further transmitted to the right association cortex via the corpus callosum. The model postulates that the apraxic disorder follows from a lesion in the left and right motor association cortices, or a disruption in their communication pathways. However this model cannot explain impaired imitation and impaired object use since these tasks do not require a verbal command (Rothi et al., 1991).

Heilman and Rothi (1993) proposed an alternative representational model of apraxia, according to which apraxia is a gesture production deficit that may result from the destruction of the spatiotemporal representations of learned movements stored in the left inferior-parietal lobule. They proposed to distinguish between dysfunction caused by destruction of the parietal areas (where the spatiotemporal representations of movements would be encoded), and the deficit which would result from the disconnection of these parietal areas from the frontal motor areas (Heilman et al., 1982). In the first case, posterior lesions would cause a degraded memory trace of the movement and patients would not be able to correctly recognize and discriminate gestures. In the second case, anterior lesions or disconnections would only provoke a memory egress disorder. Therefore patients with a gesture production deficit with anterior and posterior lesions should perform differently on tasks of gesture discrimination, gesture recognition and novel gesture learning.

Table 1. Taxonomy of apraxia

Type of apraxia	Definition
Ideational apraxia	Initially used to refer to impairment in the conceptual organization of actions, assessed with sequential use of multiple objects. Later defined as conceptual apraxia.
Conceptual apraxia	Impairment in the concept of a single action, characterized by content errors and the inability to use tools.
Ideomotor apraxia	Impairment in the performance of skilled movements, characterized by spatial or temporal errors in the execution of movements.
Limb-kinetic apraxia	Slowness and stiffness of movements with a loss of fine, precise and independent movement of the fingers.
Constructional apraxia	Difficulty in drawing and constructing objects. Impairment in the combinatory or organizing activity in which details and relationship among the component parts of the entity must be clearly perceived.
Developmental dyspraxia	Disorders affecting the initiation, organization and performance of actions in children.
Modality-specific apraxias	*Localized within one sensory system.*
Pantomime agnosia	Normal performance in gesture production tests both on imitation and on verbal command, but poor performance in gesture discrimination and comprehension. Patients with pantomime agnosia can imitate pantomimes they cannot recognize.
Conduction apraxia	Superior performance on pantomime to verbal command than on pantomime imitation.
Visuo-imitative apraxia	Normal performance on verbal command with selectively impaired imitation of gestures. Also used to designate the defective imitation of meaningless gestures combined with preserved imitation of meaningful gestures.
Optical (or visuomotor) apraxia	Disruptions to actions calling upon underlying visual support.
Tactile apraxia	Disturbance of transitive hand movements for use of, recognition and interaction with an object, in the presence of preserved intransitive movements.
Effector-specific apraxias	
Upper/lower face apraxia	Impairment in performing actions with parts of the face.
Oral apraxia	Inability to perform skilled movements with the lips, cheeks and tongue.
Orofacial (or buccofacial) apraxia	Difficulties with performing intentional movements with facial structures including the cheeks, lips, tongue and eyebrows.
Lid apraxia	Difficulty with opening the eyelids.
Ocular apraxia	Impairment in performing saccadic eye movements on command.
Limb apraxia	Used to refer to ideomotor apraxia of the limbs frequently including the hands and fingers.
Trunk (or axial) apraxia	Difficulty with generating body postures.
Leg apraxia	Difficulty with performing intentional movements with the lower limbs.
Task-specific apraxias	
Gait apraxia	Impaired ability to execute the highly practised, co-ordinated movements of the lower legs required for walking.
Gaze apraxia	Difficulty in directing gaze.
Apraxia of speech (or verbal apraxia)	Disturbances of word articulation.
Apraxic agraphia	A condition in which motor writing is impaired but limb praxis and non-motor writing (typing, anagram letters) are preserved.
Dressing apraxia	Inability to perform the relatively complex task of dressing.
Dyssynchronous apraxia	Failure to combine simultaneous preprogrammed movements.
Orienting apraxia	Difficulty in orienting one's body with reference to other objects.
Mirror apraxia	A deficit in reaching to objects presented in a mirror.
Lesion-specific apraxias	
Callosal apraxia	Apraxia caused by damage to the anterior corpus callosum that usually affects the left limb.
Sympathetic apraxia	Apraxia of the left limb due to damage to the anterior left hemisphere (the right hand being partially or fully paralyzed).
Crossed apraxia	The unexpected pattern of apraxia of the right limb following damage to the right-hemisphere.

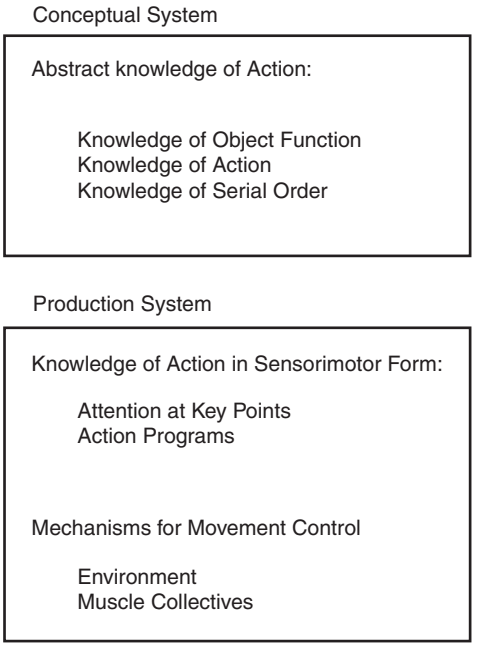

Fig. 1. Roy and Square's cognitive model of limb praxis. Adapted with permission from Roy and Square (1985).

Roy and Square (1985) proposed a cognitive model of limb praxis that involves two systems, i.e., a conceptual system and a production system (illustrated in Fig. 1). The "conceptual system" provides an abstract representation of the action and comprises three kinds of knowledge: (1) knowledge of the functions of tools and objects, (2) knowledge of actions independent of tools and objects and (3) knowledge about the organization of single actions into sequences. The "production system" incorporates a sensorimotor representation of the action and mechanisms for movement control. Empirical support for the division of the praxis system into a conceptual and a production component is provided by a patient who could comprehend and discriminate transitive gestures she was unable to perform (Rapcsak et al., 1995). This model predicts three patterns of impairment (Heath et al., 2001). First, a deficit in pantomime but not in imitation would reflect damage to the selection and/or evocation of actions from long-term memory. Second, a deficit in imitation alone would indicate a disruption of the visual gestural analysis or translation of visual information into movement. Finally, concurrent impairment in pantomime and imitation is thought to reflect a disturbance at the latter, executive stage of gesture production and was the most frequent deficit pattern observed in Roy et al. (2000) and Parakh et al. (2004).

None of these models predict a number of modality-specific dissociations observed in neurologically impaired patients, such as preserved gesture execution on verbal command that is impaired in the visual modality when imitating (Ochipa et al., 1994; Goldenberg and Hagmann, 1997). To account for these dissociations, Rothi et al. (1991) proposed a cognitive neuropsychological model of limb praxis, which reflects more appropriately the complexity of human praxis (illustrated in Fig. 2a). This multi-modular model has input that is selective according to the modality, a specific "action semantics system" dissociable from other semantics systems, an "action reception lexicon" that communicates with an "action production lexicon" and a separate "nonlexical route" for the imitation of novel and meaningless gestures[7] (Rothi et al., 1997).

Although this model is widely used to explain data from multiple neurological studies, it has difficulties concerning several aspects. First, it does not consider the existence of a selective tactile route to transitive actions (Graham et al., 1999). For example, the model fails to explain data from a patient profoundly impaired in gesturing in the verbal and visual modalities, but not with the tool in hand (Buxbaum et al., 2000). Second, imitation of meaningless gestures is assumed to test the integrity of a direct route from visual perception to motor control. However, Goldenberg et al. (1996) have shown that this route is far from direct and involves complex intermediate processing steps. For example, apraxic patients that are impaired in reproducing gestures on their own bodies are also impaired in replicating the gestures on a life-sized manikin (Goldenberg, 1995). Hence, general conceptual knowledge about the human body and the spatial configuration of body parts seems necessary for performing an imitation task (Goldenberg, 1995; Goldenberg et al., 1996;

[7]The vocabulary was borrowed from the literature of language processing.

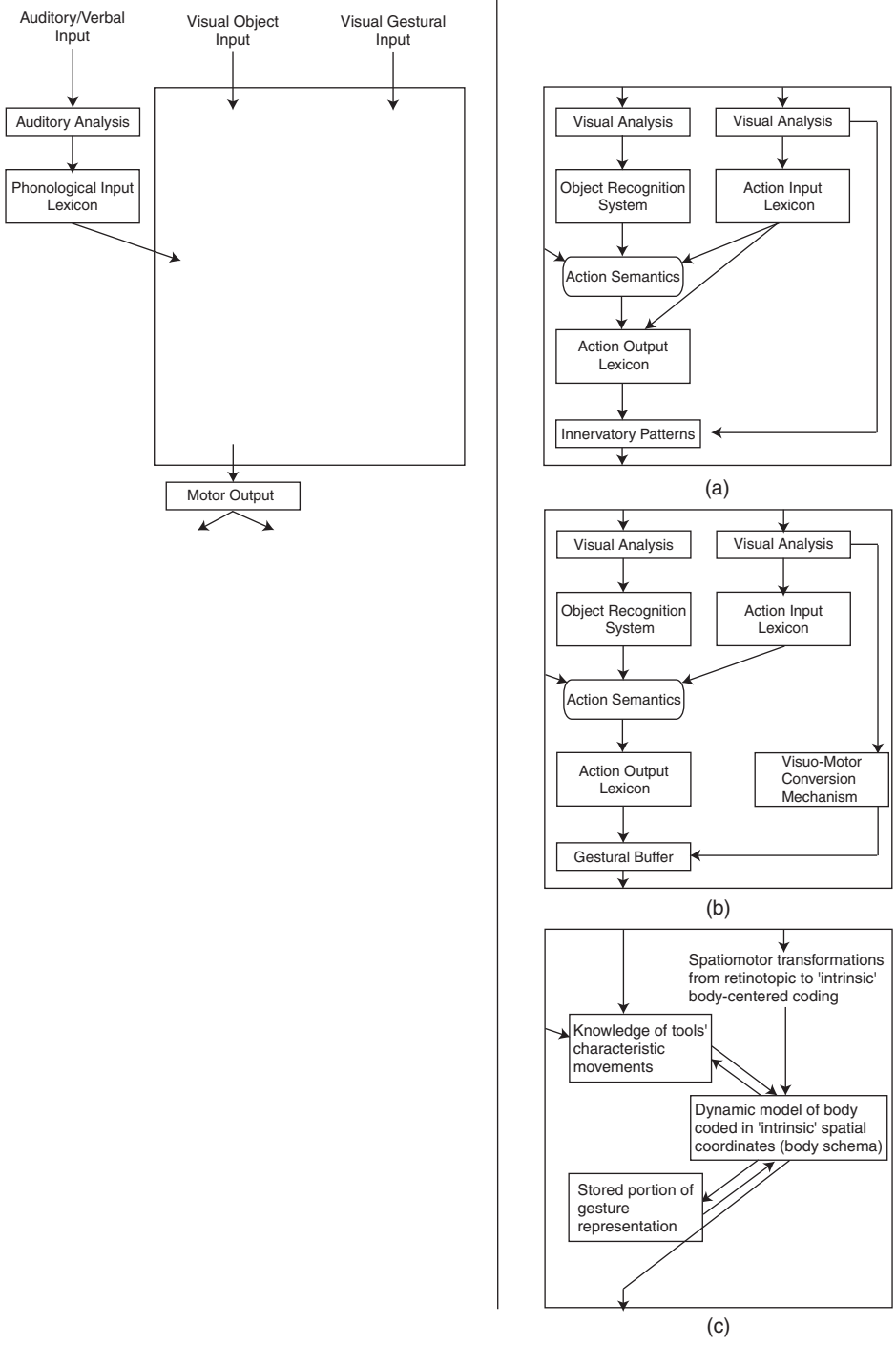

Fig. 2. A cognitive neuropsychological model of limb praxis. The three components on the right are interchangeable with the empty box in the complete model on the left. Under (a) Rothi et al.'s original model of limb praxis. Under (b) the previous model revised by Cubelli et al. and under (c) the model extended by Buxbaum et al. For a detailed description see the text. Adapted respectively with permission from Rothi et al. (1997), Cubelli et al. (2000) and Buxbaum et al. (2000).

Goldenberg and Hagmann, 1997). The belief that imitation is a rather simple and straightforward visuomotor process is misleading as one would have to resolve the "body correspondence problem"[8] to transpose movements from bodies with different sizes and different owners, which are in addition represented in different perspectives (Goldenberg, 1995).

To account for the last observation, Cubelli et al. (2000) have revised Rothi et al.'s cognitive neuropsychological model of limb praxis (illustrated in Fig. 2b). They have added "a visuomotor conversion mechanism" devoted to transcoding the visual input into appropriate motor programs. They have also suppressed the direct link between the "input" and "output action lexicon", leaving only an indirect link through the "action semantics system", as no empirical evidence was found of a patient able to reproduce familiar gestures with obscure meaning, but not unfamiliar gestures (see Fig. 2a, b). Finally, they have also added a "gestural buffer" aimed at holding a short-term representation of the whole action. The model predicts five different clinical pictures (for definitions of the different apraxic disorders please refer to Table 1): (1) a deficit of the "action input lexicon": *pantomime agnosia* (i.e., a difficulty in the discrimination and comprehension of gestures), (2) a deficit of the "action semantics system": conceptual apraxia without ideomotor apraxia, (3) a deficit of the "action output lexicon": conceptual apraxia with spared gesture-meaning associations, (4) a deficit of the "visuomotor conversion mechanism": conduction apraxia (not observed in their study) and (5) a deficit of the "gestural buffer": both ideomotor and ideational apraxia (i.e., impairment in all execution tasks with preserved ability to perform judgment and categorization tasks).

Buxbaum et al. (2000) further extended Rothi et al.'s cognitive neuropsychological model of limb praxis, based on their observation of a patient who performed particularly poorly on tasks that required a spatial transformation of the body. According to their model (illustrated in Fig. 2c), a unitary set of representations named "body schema" calculates and updates the dynamic positions of the body parts relative to one another. Importantly, this dynamic body-centered representation of actions is a common processing stage between the "lexical" and "nonlexical route" and hence subserves both meaningful and meaningless actions. Note that at the level of the "lexical route", there is an additional interaction with the stored representations of learned actions.

Existing models of apraxia still fail to account for additional empirical evidence such as, for example, the differential performance in imitation of hand postures and imitation of finger configurations shown in Goldenberg and Hagmann (1997) and Goldenberg and Karnath (2006). Furthermore, in a study of ideomotor apraxia, Buxbaum et al. (2005b) provided data which is compatible with the influential "mirror neuron hypothesis". Apraxia models cannot easily be reconciled with this hypothesis which, based upon neurophysiological observations from the monkey brain, postulates a "mirror neuron system" underlying both action recognition and action execution (Rizzolatti and Craighero, 2004). Mirror neurons are a special class of visuomotor neurons, initially discovered in area F5 of the monkey premotor cortex (see Fig. 4), which discharge both when the monkey does a particular action and when it observes another individual doing a similar action (Gallese et al., 1996; Rizzolatti and Luppino, 2001; Rizzolatti et al., 2002). Hence, the "mirror neuron system" is believed to map observed actions onto the same neural substrate used to execute these actions. As the same representations appear to subserve both action recognition and action production tasks, it would not be surprising if the perception of a movement is constrained by its executional knowledge. Related to apraxia, the "mirror neuron hypothesis" questions the separation of the "input" and "output lexicon" (Koski et al., 2002).

Contributions of the left- and right-brain hemispheres

Although most apraxia studies show a left-brain hemisphere dominance for praxis, the studies

[8]Here we give a shortened version of the informal statement of the body correspondence problem. Given an observed behavior of the model, i.e., a sequence (or hierarchy) of subgoals, find and execute a sequence of actions using one's own (possibly dissimilar) embodiment which leads through the corresponding subgoals (Nehaniv and Dautenhahn, 2002).

arguing for a significant involvement of the right hemisphere are numerous. Left-brain damage usually affects both hands, whereas right-brain damage affects only the left hand, suggesting that the left hemisphere is not only fully competent for processing movement concepts but also contributes to the generation of movements in the right hemisphere. Apraxic deficits following left hemisphere lesions are also more frequent (De Renzi et al., 1980; Weiss et al., 2001); however, in some rare cases, severe apraxia was observed following right hemisphere lesions (Marchetti and Sala, 1997; Raymer et al., 1999). The concept of crossed apraxia was introduced to describe patients with this opposite pattern of limb apraxia that cannot be explained by handedness. Callosal lesions are most suitable for investigating the issues of hemispheric specialization of praxis. For example, split-brain patients were apraxic with their left hands, also suggesting a left hemisphere dominance for processing skilled movement (Watson and Heilman, 1983; Lausberg et al., 1999, 2003), but both hemispheres appeared to contain concepts for skill acquisition (Lausberg et al., 1999) and object use (Lausberg et al., 2003).

In kinematic studies (described in more detail in "The analysis of apraxic errors"), only left-brain damaged patients were impaired in imitation of meaningless movements (Hermsdörfer et al., 1996; Weiss et al., 2001), as well as in pointing movements (Hermsdörfer et al., 2003); whereas right-brain damaged patients had deficits in slow-paced tapping and initiation of aiming movements (Haaland and Harrington, 1996). Hence, the left hemisphere was associated with movement trajectory control (Haaland et al., 2004), sequencing and ballistic movements (Hermsdörfer et al., 2003) and the right hemisphere was related to on-line control of the movement (Hermsdörfer et al., 2003) and closed-loop processing (Haaland and Harrington, 1996).

A left–right dichotomy was also observed for imitation and matching of hand and finger configurations (Goldenberg, 1999). Left-brain damaged patients had more difficulties with imitation than matching and vice versa. In addition, the left hemisphere seemed fully competent for processing hand postures, but needed the right hemisphere's contribution for processing finger postures (Goldenberg et al., 2001; Sala et al., 2006a). It was concluded that the left hemisphere mediates conceptual knowledge about the structure of the human body and that the right hemisphere is specialized for visually analyzing the gesture (Goldenberg, 2001; Goldenberg et al., 2001).

Finally, several studies observed similar impairment scores following left- and right-brain lesions, arguing for a bi-hemispheric representation of skilled movement (Haaland and Flaherty, 1984; Kertesz and Ferro, 1984; Roy et al., 1992, 2000; Heath et al., 2001). The less frequent, nevertheless well-detected incidence of limb apraxia following right-brain lesion, was attributed to the sensitivity and precision of the assessment methodology. In addition, right-hemisphere lesions often led to severe face apraxia (Bizzozero et al., 2000; Sala et al., 2006b). Hence, a model of widespread praxis, distributed across both hemispheres, may be more appropriate than the unique left-lateralized center previously hypothesized. Moreover, it seems that the degree of left-hemisphere dominance varies within subjects and with the type of movement (Haaland et al., 2004), raising the issue of overlap between the contributions of the right and left hemispheres to specialized praxic functions.

Intra-hemispheric lesion location: a distributed representation of praxis?

Several studies have failed to find a consistent association between the locus of the lesion within a hemisphere and the severity of apraxia (Basso et al., 1980; Kertesz and Ferro, 1984; Alexander et al., 1992; Schnider et al., 1997; Hermsdörfer et al., 2003). Moreover, areas involved in apraxia can also be damaged in non-apraxic patients (Haaland et al., 1999; Buxbaum et al., 2003). However, apraxic deficits are most frequent following parietal and frontal lesions, but were also observed in patients with temporal, occipital and subcortical damages (De Renzi and Lucchelli, 1988; Goldenberg, 1995; Hermsdörfer et al., 1996; Bizzozero et al., 2000).

More specifically, ideomotor apraxia and motor imagery deficits were observed following lesions in the left inferior parietal and the left dorsolateral frontal lobes (Haaland et al., 2000; Buxbaum et al.,

2005a). For example, several studies suggested that Brodmann areas 39 and 40 (i.e., angular and supramarginal gyri of the inferior-parietal lobule) are critical in visuo-imitative apraxia (Goldenberg and Hagmann, 1997; Goldenberg, 2001) and ideomotor limb apraxia (Haaland et al., 1999; Buxbaum et al., 2003). In addition, the superior-parietal lobe appeared crucial in integrating external visual and intra-personal somaesthisic information (Heilman et al., 1986; Haaland et al., 1999). Goldenberg and Karnath (2006), subtracted the lesion overlay of unimpaired from impaired patients and associated disturbed imitation of hand postures with lesions in the inferior-parietal lobe and temporo–parieto–occipital junction, whereas disturbed imitation of finger postures could be related to lesions in the inferior frontal gyrus. Interestingly, parts of the middle and inferior frontal gyri, in the vicinity of Brodmann areas 6, 8 and 46, were involved in all of the ideomotor apraxics in Haaland et al. (1999). Furthermore, premotor lesions (including lesions to the supplementary motor area) particularly affected bimanual actions in Halsband et al. (2001) and transitive actions in Watson et al. (1986).

It has been difficult to disentangle between the specific contributions of the parietal and the frontal cortices, as lesions in these areas lead to similar deficits (Haaland et al., 1999, 2000). For example, target and spatial errors were related to posterior lesions only (Haaland et al., 2000; Halsband et al., 2001; Weiss et al., 2001; Goldenberg and Karnath, 2006), but internal hand configuration errors were present in patients with anterior and posterior lesions (Haaland et al., 2000; Goldenberg and Karnath, 2006). Importantly, only patients with posterior lesions, and not anterior lesions, had difficulties in discriminating between correctly and incorrectly performed actions and in recognizing pantomimes or appropriate hand postures (Halsband et al., 2001; Buxbaum et al., 2005b).

Apraxia can also develop following subcortical lesions (Pramstaller and Marsden, 1996; Graham et al., 1999; Jacobs et al., 1999; Merians et al., 1999; Hanna-Pladdy et al., 2001). In this case, it is not clear whether the apraxia originates from lesions in the basal ganglia, which are extensively connected to the superior-parietal lobe and premotor and supplementary motor areas (Jacobs et al., 1999; Merians et al., 1999), or from the surrounding white matter (i.e., fronto-parietal connections) (Pramstaller and Marsden, 1996).

Failure to find clear correlations between specific lesion loci and different apraxic deficits argues for a widespread cortical and subcortical representation of praxis, distributed across specialized neural systems working in concert (Leiguarda and Marsden, 2000; Hermsdörfer et al., 2003). However, we believe that a selective damage to one of these systems may produce a particular pattern of errors tightly related to a subtype of apraxia.

Praxis and language?

Apraxia is most often seen in association with aphasia (i.e., loss of the ability to speak or understand speech), which renders the assessment of apraxia very difficult. Indeed, one has to provide evidence that the patient has understood the commands so that the motor deficit cannot be attributed to aphasia (De Renzi et al., 1980). Historically, gestural disturbance in aphasics was considered to be a manifestation of damaged abstract knowledge. This idea of a common impaired symbolic function underlying aphasia and apraxia was supported for a long time (Kertesz and Hooper, 1982). However, several large-scale studies failed to find correlations between subtypes of apraxia and aphasia (Goodglass and Kaplan, 1963; Lehmkuhl et al., 1983; Buxbaum et al., 2005b). Moreover, clear evidence of a double dissociation between apraxia and aphasia was presented in Papagno et al. (1993). For example, some patients were able to verbalize a desired movement but could not perform it (Goodglass and Kaplan, 1963), whereas other patients were able to pantomime actions they were unable to name (Rothi et al., 1991). Hence, it seems that many aspects of language and praxis are subserved by independent, possibly contiguous neuronal processes, but concomitant deficits may also appear because of shared neuroanatomical substrates (Kertesz and Hooper, 1982). Nevertheless, the question of how language is related to praxis is a fascinating one and needs further study, as it can give some insight into the existence of a supramodal representation of knowledge, or alternatively shed light onto the communication

mechanisms between the praxic- and language-specific representations of knowledge.[9]

The analysis of apraxic errors

There are extensive quantitative analyses of the severity of apraxic errors in single case studies and in large samples of brain-damaged patients. Qualitative analyses however are less numerous and non-standardized, but nonetheless essential for precisely understanding the nature of apraxia. Performances are usually classified in a limited number of response categories such as:[10] temporal errors, spatial errors, content errors, substitutive errors, augmentative errors, fragmentary errors, associative errors (i.e., the correct movement is replaced by another movement that shares one feature), parapraxic errors (i.e., correct execution of a wrong movement), wrong body part errors (e.g., patients that execute a correct movement with the head instead of the hand), body part as tool errors (i.e., a body part is used to represent the imagined tool) and perseveration errors (Lehmkuhl et al., 1983; Poeck, 1983; De Renzi and Lucchelli, 1988; Platz and Mauritz, 1995; Lausberg et al., 1999, 2003; Halsband et al., 2001; Weiss et al., 2001). Perseveration and body parts as tool errors should be accorded some special interest in future studies, as they are prominent in apraxia and their occurrence is far from being elucidated (Poeck, 1983; Raymer et al., 1997; Lausberg et al., 2003). For example, even though normal subjects also commit body part as tool errors,[11] only subjects with brain lesion cannot correct their error after re-instruction (Raymer et al., 1997).

A significant step forward in the analysis of apraxic errors was the use of quantitative 3D kinematic motion analysis. These techniques allowed to show many abnormalities in the kinematic features of apraxic movements such as: deficits in spatial accuracy, irregular velocity profiles, reduced maximum velocities, reduced movement amplitudes, de-coupling of the relationship between instantaneous wrist velocity and trajectory curvature, improper linearity of the movement, wrong orientation of the movement in space and/or deficient joint coordination (Poizner et al., 1990, 1995, 1997; Clark et al., 1994; Platz and Mauritz, 1995; Rapcsak et al., 1995; Merians et al., 1997, 1999; Haaland et al., 1999; Binkofski et al., 2001; Hermsdörfer et al., 2006). An example of an apraxic movement with abnormal kinematics is shown in Fig. 3. Based on kinematic studies it could be concluded that ideomotor limb apraxia impaired the response implementation but not the preprogramming of the movement (Haaland et al., 1999) and decoupled the spatial and temporal representations of the movement (Poizner et al., 1990, 1995). Importantly, the kinematic abnormalities observed were often spatial and not temporal, the longer movement times in the apraxic group could be interpreted as an artifact of the longer distance traveled (Haaland et al., 1999; Hermsdörfer et al., 2006). However, several authors have advised against systematically interpreting the irregular kinematics as an indicator for deficient motor programming or deficient motor implementation (Platz and Mauritz, 1995; Haaland et al., 1999). For example, no correlation could be found between the kinematic abnormalities and apraxic errors in Hermsdörfer et al. (1996). Indeed, movements with degraded kinematics frequently reached a correct final position, while, on the contrary, kinematically normal movements often led to apraxic errors. The abnormal kinematic profile of the gesture probably arose from several corrective and compensatory strategies that the patient used to cope with the apraxic deficit (Goldenberg et al., 1996; Hermsdörfer et al., 1996). For example, hesitant and on-line controlled movements generated multi-peaked velocity profiles in our study (see Fig. 3d). Hence, according to the authors, the basic deficit underlying apraxia may concern the mental representation of the target position. Consistently with this hypothesis, it was found that apraxic

[9]Some authors have posited that an action–recognition mechanism might be at the basis of language development (Rizzolatti and Arbib, 1998).

[10]This list is not extensive. Terminologies can vary a lot across different authors.

[11]There is a hierarchical organization in the performance of actions with increasing difficulty. Children first acquire the ability to actually use objects, then to demonstrate the action with similar substitute objects, then with dissimilar substitute objects, then to use body parts as substitutes, and finally to perform pantomimes with holding imagined objects. This note was taken from Lausberg et al. (2003).

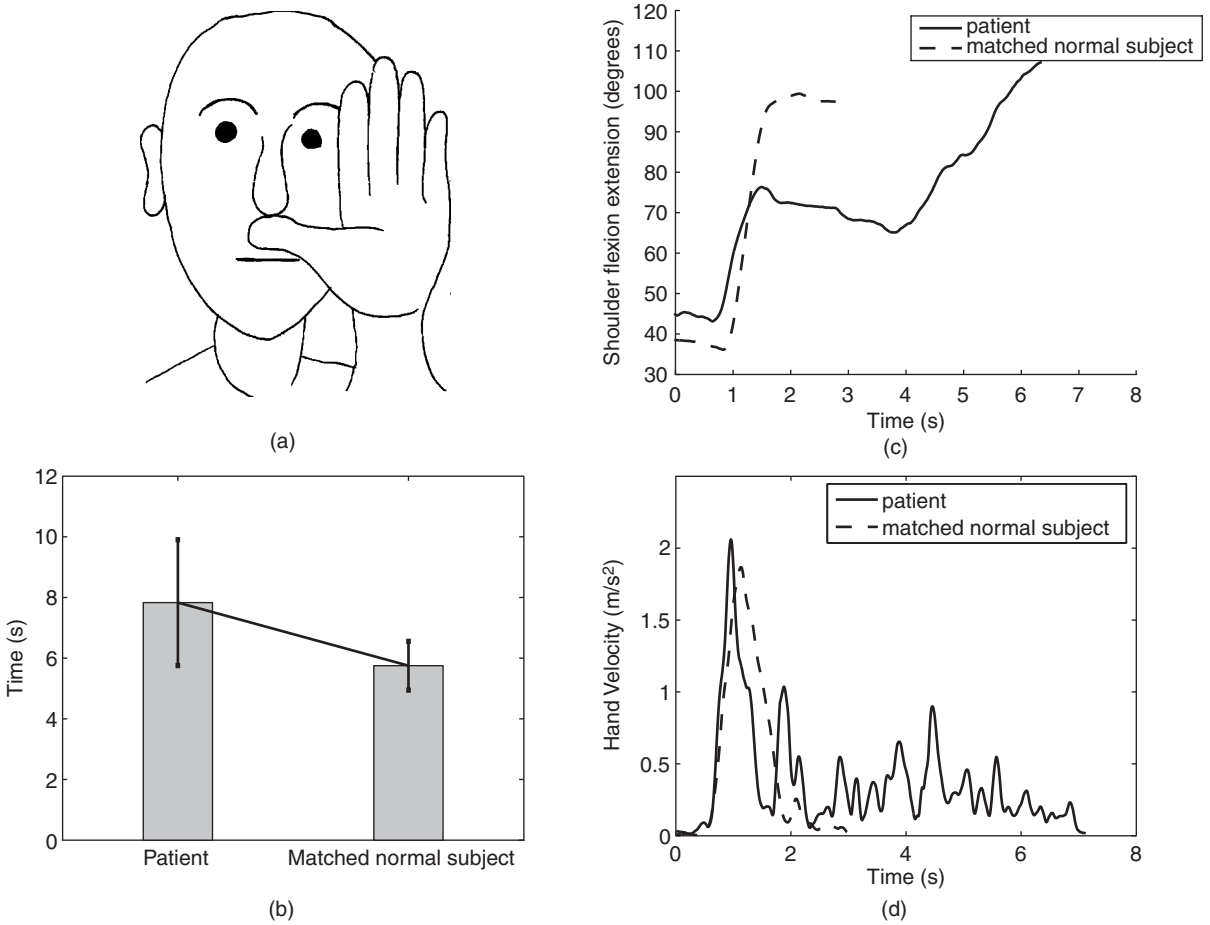

Fig. 3. An example of the abnormal kinematics of an apraxic movement. A patient with left ischemic lesions was tested in a study of imitation of meaningless gestures. The stimulus to imitate for this movement is shown under (a) and represents a hand posture relative to the head. Under (b), the movement times of the patient are longer than those of a matched normal subject (including replacement of the hand in the initial condition). Under (c), the trajectory of the shoulder flexion-extension joint angle of the patient (shown in solid line) contains several irregularities, which are the result from multiple hesitations and changes of directions, whereas the matched normal subject shoulder flexion-extension trajectory (dashed line) is smooth. The speed profile of the patient (solid line) is shown under (d) and contains multiple peaks with reduced maximum velocities that contrast with the simple bell-shaped velocity profile of the matched normal subject (dashed line).

patients relied more than normal subjects on on-line visual information in aiming movements (Ietswaart et al., 2006).

Discussion

We have shown in the preceding sections that apraxia has proven very difficult to assess and understand. Here we will try to provide some hypotheses on why these difficulties might arise and we propose several ways to overcome these.

The complex nature of apraxia

Apraxia designates the impairment of the human praxis system following brain lesion and has to deal with the high complexity and wide range of human praxic functions. Therefore studies of

apraxia have separately tackled the faulty execution of many types of gestures (e.g., transitive and intransitive, meaningful and meaningless, peripersonal and body-centered, etc.) of various end-effectors (e.g., mouth, face, leg, limb) in different types of modalities (e.g., visual, auditive, tactile presentation and imitation). The high dimensionality of varying parameters has led to a lack of systematicity in the apraxia assessment and terminologies used. This has also rendered the coherent interpretation of the disorder rather arduous.

It follows that there is a great need to discriminate between different types of actions, as they appear to be differentially impaired in apraxia and hence may involve distinct underlying mechanisms (see "Types of apraxia"). Indeed, it is very likely that the mechanisms of imitation and execution of movements vary according to the type of action that is imitated or executed (Schnider et al., 1997; Goldenberg, 1999; Goldenberg and Karnath, 2006). This suggests that different categories of actions require the use of separate systems at some stage of processing, but the level of separation between the representations underlying actions of different types, or even different actions of the same type, is not at all clear yet.

We will principally argue that it is important to better understand what a particular gesture or execution modality implies in terms of brain resources and brain processes when compared to another gesture/execution modality. For example, a transitive action, i.e., an action that involves an object, is very different from an intransitive action in the sense that it provides supplementary tactile input as a result from the interaction with the object. This tactile sensory input then needs to be integrated to the representation of the action that relies also on other types of sensory inputs such as visual and proprioceptive. Moreover, executing a transitive action in a pantomime condition is also different from executing it with the object in hand, since the action has to be retrieved without the help of tactile input produced by the object. Indeed the movement is somehow modified, for example movement amplitudes in normal subjects were larger in the pantomime condition when compared to actual sawing (Hermsdörfer et al., 2006).

The distinction between meaningful and meaningless gestures would also need some clarification. The reproduction of a recognized meaningful gesture on the one hand, appears entirely based on the internal representation of the gesture. Indeed, the knowledge of a learned skilled act is preferably retrieved from motor memory rather than being constructed *de novo* (Halsband et al., 2001). On the other hand, the reproduction of a meaningless gesture involves a close visual tracking of the imitatee's body configuration and was modeled by a "visuomotor conversion mechanism" or a "body schema" (see Fig. 2b, c). To summarize, a meaningful gesture seems to be, to a certain extent, assimilated to a goal that guides the action from memory, whereas a meaningless gesture is defined as a particular configuration of the body in space and time, with no external referents (Goldenberg, 2001). Hence, imitation of meaningless gestures might be used to test the comprehension and replication of changing relationships between the multiple parts and subdivisions of the refined and complex mechanical device, which is the human body (Goldenberg, 2001). Furthermore, a preserved imitation of meaningless gestures is crucial for the apraxic patient as it might be useful for relearning motor skills. The double dissociation observed between imitation of meaningless and meaningful gestures argues for completely separate processing systems, and is still not accounted for by any of the existing apraxia models previously described. However, meaningless actions involve novel motor sequences that must be analyzed and constructed from the existing movements (Koski et al., 2002) and both meaningless and meaningful gestures appear to engage the body schema, i.e., a dynamic model for coding the body (Buxbaum et al., 2000). Hence, meaningless and meaningful actions may also share some overlapping conceptual representations.

These examples show that there are some common and some distinct processes involved in the different types of movements and modalities used for testing apraxia. Identifying the overlap of these processes would provide a clearer framework for interpreting the patient's performance and would simplify the analysis of the lesion correlates. The choice of the testing condition is crucial, as well as identifying the processes inherent to the chosen

condition. However this is a difficult task, since correlations can be found between some very different and even dissociated types of movements.[12] For example, kinematic measures of pointing movements were correlated to gesture imitation, suggesting that the kinematic deficits observed during pointing movements are generalized to more global aiming movements, including movements for imitating hand gestures (Hermsdörfer et al., 2003). Accordingly, gesture imitation is believed to depend upon some of the same cognitive mechanisms as reaching and grasping (Haaland et al., 2000), however the level and extent of interplay is not clear. To make the picture even more complex, the underlying representations may be componential, for example with separate hand posture representations for transitive gestures (Buxbaum et al., 2005b). This leads us to two questions that urge to be answered: (1) What are the basic motor primitives from which all movements are constructed? and (2) Which are the motor components that are related to specific movements?

Beyond the complex nature of apraxia

One way to cope with the complex nature of apraxia is to be even more *precise* and *systematic* in assessing the apraxic disorder. Ideally, the full range of praxic functions, related to different effectors, including mouth, face and foot should be tested in a complete set of modalities (Koski et al., 2002). Moreover, we find it unfortunate that qualitative measures of the errors, such as kinematic measures of the movement trajectory (refer to "The analysis of apraxic errors"), are frequently missing or given in a purely statistical fashion (e.g., 25% of errors in Condition A). As such, these measures do not suffice to understand why the patient succeeds at the execution of some actions, but not other similar actions. For example, in one study the patient was able to evoke some actions (using a razor and a comb) fairly consistently, yet others (hammering and writing) were never produced (Graham et al., 1999). In another study, the same gestures were not always congruently disturbed across the different modes of execution, namely on imitation and on verbal command (Jacobs et al., 1999). We believe that it is this inability to distinguish between different types of errors related to different types of gestures that has prevented us so far from discovering the precise neuroanatomical correlates of apraxia, on top of the difficulty to accurately identify the brain lesion. Hence, the typology and analysis of apraxic errors need to be improved. We encourage extensive categorization of the errors and their characterization via kinematic methods. In addition, the errors should be reported *in relation to* the exact movement and not only specific condition tested.

We also suggest that studies that assess apraxia should more often integrate tasks of motor learning, as patients with apraxia may also be deficient in learning new motor tasks (Heilman et al., 1975; Rothi and Heilman, 1984; Platz and Mauritz, 1995; Lausberg et al., 1999). The main motivation in understanding apraxia is to help the apraxic patients in their everyday lives through the development of efficient rehabilitation methods and training programs.[13] Assessing the exact expression of the apraxic deficit, and especially the patient's motor learning abilities, would help to choose an appropriate therapy for the patient. Efficiently targeting the movements and praxis components specifically affected in each patient would accelerate the process of improving his or her praxic faculties. For the moment, apraxia in relation to motor learning is an under-investigated line of research.

Furthermore, we believe that modeling research may prove very helpful to gain some insight into the details and potential implementation of the processes underlying human praxis. When a roboticist searches for an algorithm for his robot to manipulate objects, he or she has to provide with all the different input signals and implement in practice all the necessary computations and

[12] Surprisingly, single finger tapping was a better predictor of the severity of apraxia than goal-directed grasping and aiming (Ietswaart et al., 2006). Single finger tapping is almost never used to assess apraxia.

[13] According to Platz and Mauritz (1995), only patients with ideomotor apraxia and not ideational and constructional apraxia could benefit from a task-specific sensorimotor training.

processing resources. For example, the differences and similarities between reaching to body-centered versus peripersonal cues would become evident through the development of corresponding algorithms, as they would be explicitly computed. According to Schaal and Schweighofer (2005), computational models of motor control in humans and robots often provide solid foundations that can help us to ground the vast amount of neuroscientific data that is collected today. Thus, biologically inspired modeling studies such as Sauser and Billard (2006) and Hersch and Billard (2006) seem to be very promising approaches in the understanding of the nature of gestures and in emphasizing the differences and similarities of their underlying processes.

Although neuropsychological models are essential for the understanding of apraxia, they do not address the question of the precise neural representation of the action and how this representation can be accessed. In a neurocomputational model, one has to take into account the computational principles of movement that reproduce the behavioral and kinematic results of the patient, as well as propose a biologically plausible implementation of the black-box components of apraxia models. In this view, we have a developed a simple neurocomputational model described in Petreska and Billard (2006), that accounts for the callosal apraxic deficit observed in a seminal experimental study of imitation of meaningless gestures (Goldenberg et al., 2001). Our model combines two computational methods for unsupervised learning applied to a series of artificial neural networks. The biologically inspired and distributed representations of sensory inputs self-organize according to Kohonen's algorithm (Kohonen, 2001) and associate with antihebbian learning (Gerstner and Kistler, 2002). The appropriate transformations between sensory inputs needed to reproduce certain gestures are thus learned within a biologically plausible framework. It is also possible to impair the networks in a way that accounts for the performance of Goldenberg et al.'s apraxic patient in all of the conditions of the study. The model also suggests potential neuroanatomical substrates for this task. We believe that the development of neurocomputational models is a good way to probe our understanding of apraxia and is compatible with the view of integrating knowledge from different lines of research, a point that we will defend in the following section.

Toward a multidisciplinary approach

We believe that apraxia can be best dismantled by adopting a multidisciplinary approach. Future models of apraxia will need to encompass knowledge and data from studies of *normal human motor control*, human brain imaging and monkey brain neurophysiology. Fortunately, several authors have already attempted to combine different sources of evidence: by considering apraxia in the neurophysiological framework (e.g., Leiguarda and Marsden, 2000) or by validating a model of apraxia using neuroimaging methods (e.g., Hermsdörfer et al., 2001; Peigneux et al., 2004; Chaminade et al., 2005; Mühlau et al., 2005).

Normal human motor control has been extensively studied via behavioral, psychophysical, kinematic or computational methods for decades, giving rise to several principles of movement, such as: spatial control of arm movements (Morasso, 1981), maps of convergent force fields (Bizzi et al., 1991), uncontrolled manifold concepts (Scholz and Schöner, 1999), τ-coupling in the perceptual guidance of movements (Lee et al., 1999) and inverse and forward internal models (Wolpert and Ghahramani, 2000). Studies of motor control have also inspired several models for reaching like: minimum jerk trajectory control (Flash and Hogan, 1985), vector-integration-to-endpoint model (Bullock and Grossberg, 1988), minimum torque change model (Uno et al., 1989) and stochastic optimal feedback control (Todorov and Jordan, 2002) (for a review refer to Desmurget et al. (1998)). Proposed models for grasping (e.g., schema design (Oztop and Arbib, 2002)) are reviewed in Jeannerod et al. (1995) and models for sensorimotor learning (such as the modular selection and identification for control model (Haruno et al., 2001)) in Wolpert et al. (2001). In addition, it was also shown that the amplitude and direction of pointing movements may be independently processed (Vindras et al., 2005) or that the kinematics and dynamics for

reaching may be separately learned (Krakauer et al., 1999). Investigation of apraxia can only benefit from taking into account the rich knowledge of the computational processes of movement used by the brain; and obviously, apraxia models would need to be compatible with the current general theories of movement control.

Progress in describing the contribution of specific brain regions to human praxis through the study of brain-damaged patients has been limited by the variability in the size, location and structures affected by the lesion (Koski et al., 2002). *Human brain imaging studies*, particularly positron emission tomography (PET) and functional magnetic resonance (fMRI) overcome this difficulty to a certain extent and have an essential role in resolving the neuroanatomical correlates of human functions. Despite the evident difficulties and limitations to study movements with neuroimaging, numerous studies have addressed the question of the representation of human praxis, making significant contributions to the understanding of the neural substrates underlying visuomotor control (for a review see Culham et al. (2006)). In order to give an idea of the number of praxis functions that have been addressed with brain imaging technologies, we will mention some of them: observation of meaningful and meaningless actions with the intent to recognize or imitate (Decety et al., 1997), hand imitation (Krams et al., 1998), visually guided reaching (Kertzman et al., 1997; Desmurget et al., 1999; Grefkes et al., 2004), object manipulation and tool-use (Binkofski et al., 1999; Johnson-Frey et al., 2005), real and/or imagined pantomimes (Moll et al., 2000; Choi et al., 2001; Rumiati et al., 2004) and sequential organization of actions (Ruby et al., 2002). The areas specialized for the perception of body parts and postures have been consistently identified[14] (Peigneux et al., 2000; Downing et al., 2001). Most importantly, several brain imaging studies have been conducted in relation to apraxia (Hermsdörfer et al., 2001; Peigneux et al., 2004; Chaminade et al., 2005; Mühlau et al., 2005) with the intent to test the neuroanatomical hypothesis of the neuropsychological models previously described.

Neurophysiological studies allow the investigation of brain processes at the neuronal level and are essential to the understanding of the principles of neural computation. Certainly the monkey brain differs from the human brain, however this discrepancy can be overcome to some extent through the search of homologies (Rizzolatti et al., 2002; Arbib and Bota, 2003; Orban et al., 2004; Sereno and Tootell, 2005). Sensorimotor processes such as reaching and grasping for example, have been extensively studied: several parallel parietofrontal circuits were identified, each subserving a particular sensorimotor transformation (Kalaska et al., 1997; Wise et al., 1997; Matelli and Luppino, 2001; Battaglia-Mayer et al., 2003). Without going into the details of the representations used in each of these functionally distinct parietal and frontal areas (illustrated in Fig. 4), we will mention those that seem relevant for understanding apraxia. For example, LIP-FEF neurons discharge in relation with eye movements and are sensitive to the direction and amplitude of eye saccades (Platt and Glimcher, 1998), VIP-F4 neurons construct a representation of the "peripersonal space" confined to the head (Duhamel et al., 1998), MIP-F2 neurons have a crucial role in the planning, execution and monitoring of reaching movements (Eskandar et Assad, 1999; Simon et al., 2002; Raos et al., 2004) and finally AIP-F5 neurons mediate motor responses selective for hand manipulation and grasping movements (Cohen and Andersen, 2002). Furthermore, multiple space representations appear to coexist in the brain that integrate multisensory inputs (e.g., visual, somatosensory, auditory and vestibular inputs) (Graziano and Gross, 1998). For example, neurons in area 5 appear to combine visual and somatosensory signals in order to monitor the configuration of the limbs (Graziano et al., 2000) and the receptive fields of VIP neurons respond congruently (i.e., with matching receptive fields) to tactile and visual stimulation (Duhamel et al., 1998). It is very interesting that the modality-specific activities are spatially aligned: the visual receptive field corresponding to the arm or the face may shift along with that body part when it is passively

[14]Interestingly, these occipital and visually specialized areas are not only modulated by the visual presentation of body configurations, but also when the person executes a limb movement (Astafiev et al., 2004), indicating a bi-directional flow of the information.

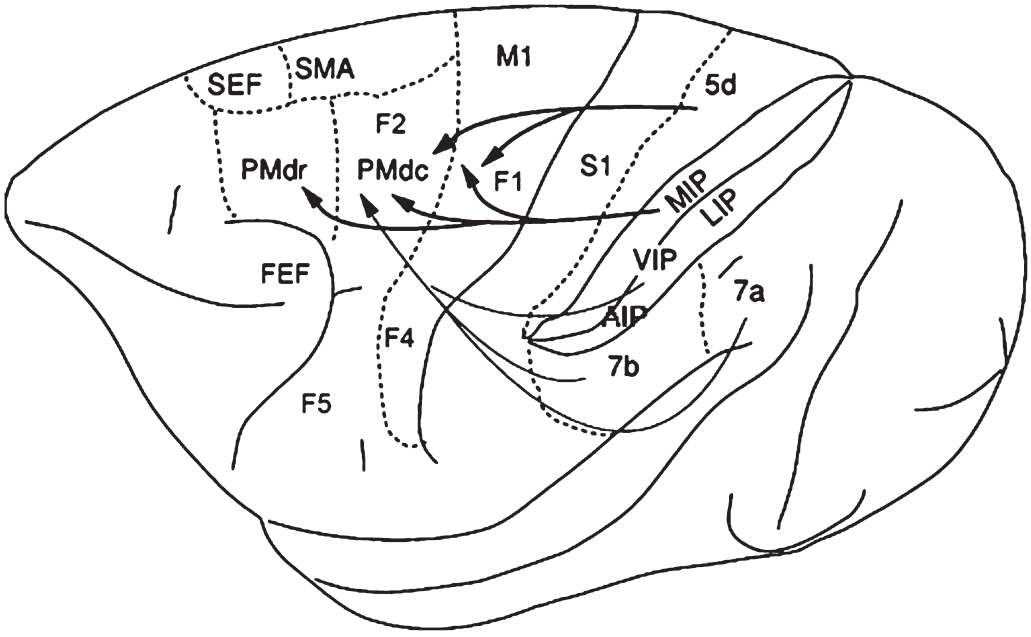

Fig. 4. Schema of the monkey brain areas and their connectivity. Adapted with permission from Wise et al. (1997).

moved (Graziano et al., 1997). In addition, neurophysiological data can give us insight into how the arm posture modulates the activity of somatosensory neurons (Helms Tillery et al., 1996) and how it affects the neurons that compute the trajectory of the hand (Scott et al., 1997). It should be noted that several sensorimotor transformations are needed in order to grasp an object, the motor command being in hand coordinates and the object's location in gaze coordinates. To compute these transformations, the brain appears to use multiple body-centered frames of references (Graziano and Gross, 1998): the frames of references underlying VIP area neurons appear to be organized along a continuum from eye to head coordinates (Duhamel et al., 1997; Avillac et al., 2005) and direct transformations from head to body-centered representations are possible in the posterior-parietal cortex (Buneo et al., 2002; Buneo and Andersen, 2006) with an error estimate of the target position computed in a common eye reference frame (Batista et al., 2002; Cohen and Andersen, 2002). Finally, it was also shown that tools may be integrated into the "body schema" at the neuronal level (Iriki et al., 1996; Maravita et al., 2003).

To conclude, we strongly believe that this multidisciplinary approach should be *bidirectional*. Not only apraxia can be interpreted in the neuropsychological and neurophysiological frameworks, but these research domains would also benefit from taking into consideration observations from apraxia. For example, one could learn enormously on how the normal human praxis system functions by looking at how it is affected by apraxia.

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References

Alexander, M.P., Baker, E., Naeser, M.A., Kaplan, E. and Palumbo, C. (1992) Neuropsychological and neuroanatomical dimensions of ideomotor apraxia. Brain, 115: 87–107.

Arbib, M. and Bota, M. (2003) Language evolution: neural homologies and neuroinformatics. Neural Netw., 16: 1237–1260.

Astafiev, S.V., Stanley, C.M., Shulman, G.L. and Corbetta, M. (2004) Extrastriate body area in human occipital cortex responds to the performance of motor actions. Nat. Neurosci., 7(5): 542–548.

Avillac, M., Denève, S., Olivier, E., Pouget, A. and Duhamel, J.-R. (2005) Reference frames for representing visual and tactile locations in parietal cortex. Nat. Neurosci., 8(7): 941–949.

Bartolo, A., Cubelli, R., Sala, S.D., Drei, S. and Marchetti, C. (2001) Double dissociation between meaningful and meaningless gesture reproduction in apraxia. Cortex, 37: 696–699.

Basso, A., Luzzatti, C. and Spinnler, H. (1980) Is ideomotor apraxia the outcome of damage to well-defined regions of the left hemisphere? Neuropsychological study of CAT correlation. J. Neurol. Neurosurg. Psychiatry, 43: 118–126.

Batista, A.P., Buneo, C.A., Snyder, L.H. and Andersen, R.A. (1999) Reach plans in eye-centered coordinates. Science, 285(5425): 257–260.

Battaglia-Mayer, A., Caminiti, R., Lacquiniti, F. and Zago, M. (2003) Multiple levels of representation of reaching in the parieto-frontal network. Cereb. Cortex, 13: 1009–1022.

Binkofski, F., Buccino, G., Stephan, K.M., Rizzolatti, G., Seitz, R.J. and Freund, H.-J. (1999) A parieto-premotor network for object manipulation: evidence from neuroimaging. Exp. Brain Res., 128: 210–213.

Binkofski, F., Butler, A., Buccino, G., Heide, W., Fink, G., Freund, H.-J. and Seitz, R.J. (2003) Mirror apraxia affects the peripersonal mirror space. A combined lesion and cerebral activation study. Exp. Brain Res., 153: 210–219.

Binkofski, F., Kunesch, E., Classen, J., Seitz, R.J. and Freund, H.-J. (2001) Tactile apraxia: Unimodal apractic disorder of tactile object exploration associated with parietal lobe lesions. Brain, 124: 132–144.

Bizzi, E., Mussa-Ivaldi, F.A. and Giszter, S. (1991) Computations underlying the execution of movement: a biological perspective. Science, 253: 287–291.

Bizzozero, I., Costato, D., Sala, S.D., Papagno, C., Spinnler, H. and Venneri, A. (2000) Upper and lower face apraxia: role of the right hemisphere. Brain, 123: 2213–2230.

Bullock, D. and Grossberg, S. (1988) Neural dynamics of planned arm movements: emergent invariants and speed-accuracy properties during trajectory formation. Psychol. Rev., 95(1): 49–90.

Buneo, C.A. and Andersen, R.A. (2006) The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements. Neuropsychologia, 44(13): 2594–2606.

Buneo, C.A., Jarvis, M.R., Batista, A.P. and Andersen, R.A. (2002) Direct visuomotor transformations for reaching. Nature, 416: 632–635.

Buxbaum, L.J., Giovannetti, T. and Libon, D. (2000) The role of dynamic body schema in praxis: evidence from primary progressive apraxia. Brain Cogn., 44: 166–191.

Buxbaum, L.J., Johnson-Frey, S.H. and Bartlett-Williams, M. (2005a) Deficient internal models for planning hand–object interactions in apraxia. Neuropsychologia, 43: 917–929.

Buxbaum, L.J., Kyle, K.M. and Menon, R. (2005b) On beyond mirror neurons: internal representations subserving imitation and recognition of skilled object-related actions in humans. Brain Res. Cogn. Brain Res., 25: 226–239.

Buxbaum, L.J., Sirigu, A., Schwartz, M.F. and Klatzky, R. (2003) Cognitive representations of hand posture in ideomotor apraxia. Neuropsychologia, 41: 1091–1113.

Cermak, S. (1985) Developmental dyspraxia. In: Roy E.A. (Ed.), Neuropsychological Studies of Apraxia and Related Disorders. North-Holland, Amsterdam, pp. 225–248.

Chaminade, T., Meltzoff, A.N. and Decety, J. (2005) An fMRI study of imitation: action representation and body schema. Neuropsychologia, 43(2): 115–127.

Choi, S.H., Na, D.L., Kang, E., Lee, K.M., Lee, S.W. and Na, D.G. (2001) Functional magnetic resonance imaging during pantomiming tool-use gestures. Exp. Brain Res., 139(3): 311–317.

Clark, M.A., Merians, A.S., Kothari, A., Poizner, H., Macauley, B., Rothi, L.J.G. and Heilman, K.M. (1994) Spatial planning deficits in limb apraxia. Brain, 117: 1093–1106.

Cohen, Y.E. and Andersen, R.A. (2002) A common reference frame for movement plans in the posterior parietal cortex. Nat. Rev. Neurosci., 3: 553–562.

Cubelli, R., Marchetti, C., Boscolo, G. and Della Sala, S. (2000) Cognition in action: testing a model of limb apraxia. Brain Cogn., 44: 144–165.

Culham, J.C., Cavina-Pratesi, C. and Singhal, A. (2006) The role of parietal cortex in visuomotor control: what have we learned from neuroimaging? Neuropsychologia, 44(13): 2668–2684.

Decety, J., Grèzes, J., Costes, N., Jeannerod, M., Procyk, E., Grassi, E. and Fazio, F. (1997) Brain activity during observation of actions. Influence of action content and subject's strategy. Brain, 120: 1763–1777.

Della Sala, S., Faglioni, P., Motto, C. and Spinnler, H. (2006a) Hemisphere asymmetry for imitation of hand and finger movements, Goldenberg's hypothesis reworked. Neuropsychologia, 44(8): 1496–1500.

Della Sala, S., Maistrello, B., Motto, C. and Spinnler, H. (2006b) A new account of face apraxia based on a longitudinal study. Neuropsychologia, 44(7): 1159–1165.

De Renzi, E., Faglioni, P. and Sorgato, P. (1982) Modality specific and supramodal mechanisms of apraxia. Brain, 105: 301–312.

De Renzi, E. and Lucchelli, F. (1988) Ideational apraxia. Brain, 111: 1173–1185.

De Renzi, E., Motti, F. and Nichelli, P. (1980) Imitating gestures. A quantitative approach to ideomotor apraxia. Arch. Neurol., 37(1): 6–10.

Desmurget, M., Epstein, C.M., Turner, R.S., Prablanc, C., Alexander, G.E. and Grafton, S.T. (1999) Role of the posterior parietal cortex in updating reaching movements to a visual target. Nat. Neurosci., 2(6): 563–567.

Desmurget, M., Pélisson, D., Rossetti, Y. and Prablanc, C. (1998) From eye to hand: planning goal-directed movements. Neurosci. Biobehav. Rev., 22(6): 761–788.

Downing, P.E., Jiang, Y., Shuman, M. and Kanwisher, N. (2001) A cortical area selective for visual processing of the human body. Science, 293: 2470–2473.

Duhamel, J.-R., Bremmer, F., BenHamed, S. and Graf, W. (1997) Spatial invariance of visual receptive fields in parietal cortex neurons. Nature, 389: 845–848.

Duhamel, J.-R., Colby, C.L. and Goldberg, M.E. (1998) Ventral intraparietal area of the macaque: congruent visual and somatic response properties. J. Neurophysiol., 79: 126–136.

Eskandar, E.N. and Assad, J.A. (1999) Dissociation of visual, motor and predictive signals in parietal cortex during visual guidance. Nat. Neurosci., 2(1): 88–93.

Faglioni, P. and Basso, A. (1985) Historical perspectives on neuroanatomical correlates of limb apraxia. In: Roy E.A. (Ed.), Neuropsychological studies of apraxia and related disorders. North-Holland, Amsterdam, pp. 3–44.

Flash, T. and Hogan, N. (1985) The coordination of arm movements: an experimentally confirmed mathematical model. J. Neurosci., 5: 1688–1703.

Gallese, V., Fadiga, L., Fogassi, L. and Rizzolatti, G. (1996) Action recognition in the premotor cortex. Brain, 119: 593–609.

Gerstner, W. and Kistler, W. (2002) Spiking neuron models: single neurons, populations, plasticity. Cambridge University Press.

Geschwind, N. (1965) Disconnexion syndromes in animals and man. Part I. Brain, 88: 237–294.

Goldenberg, G. (1995) Imitating gestures and manipulating a mannikin — the representation of the human body in ideomotor apraxia. Neuropsychologia, 33(1): 63–72.

Goldenberg, G. (1999) Matching and imitation of hand and finger postures in patients with damage in the left or right hemispheres. Neuropsychologia, 37(5): 559–566.

Goldenberg, G. (2001) Imitation and matching of hand and finger postures. Neuroimage, 14: S132–S136.

Goldenberg, G. (2003) Apraxia and beyond: life and work of Hugo Liepmann. Cortex, 39(3): 509–524.

Goldenberg, G. and Hagmann, S. (1997) The meaning of meaningless gestures: a study of visuo-imitative apraxia. Neuropsychologia, 35(3): 333–341.

Goldenberg, G., Hermsdörfer, J. and Spatt, J. (1996) Ideomotor apraxia and cerebral dominance for motor control. Cogn. Brain Res., 3: 95–100.

Goldenberg, G. and Karnath, H.-O. (2006) The neural basis of imitation is body part specific. J. Neurosci., 26(23): 6282–6287.

Goldenberg, G., Laimgruber, K. and Hermsdörfer, J. (2001) Imitation of gestures by disconnected hemispheres. Neuropsychologia, 39: 1432–1443.

Goodglass, H. and Kaplan, E. (1963) Disturbance of gesture and pantomime in aphasia. Brain, 86: 703–720.

Graham, N.L., Zeman, A., Young, A.W., Patterson, K. and Hodges, J.R. (1999) Dyspraxia in a patient with corticobasal degeneration: the role of visual and tactile inputs to action. J. Neurol. Neurosurg. Psychiatry, 67: 334–344.

Graziano, M.S.A., Cooke, D.F. and Taylor, C.S. (2000) Coding the location of the arm by sight. Science, 290: 1782–1786.

Graziano, M.S.A. and Gross, C.G. (1998) Spatial maps for t he control of movement. Curr. Opin. Neurobiol., 8(2): 195–201.

Graziano, M.S.A., Hu, X.T. and Gross, C.G. (1997) Visuospatial properties of ventral premotor cortex. J. Neurophysiol., 77: 2268–2292.

Grefkes, C., Ritzl, A., Zilles, K. and Fink, G.R. (2004) Human medial intraparietal cortex subserves visuomotor coordinate transformation. Neuroimage, 23: 1494–1506.

Haaland, K.Y. and Flaherty, D. (1984) The different types of limb apraxia errors made by patients with left vs. right hemisphere damage. Brain Cogn., 3(4): 370–384.

Haaland, K.Y. and Harrington, D.L. (1996) Hemispheric asymmetry of movement. Curr. Opin. Neurobiol., 6: 796–800.

Haaland, K.Y., Harrington, D.L. and Knight, R.T. (1999) Spatial deficits in ideomotor limb apraxia. A kinematic analysis of aiming movements. Brain, 122: 1169–1182.

Haaland, K.Y., Harrington, D.L. and Knight, R.T. (2000) Neural represantations of skilled movement. Brain, 123: 2306–2313.

Haaland, K.Y., Prestopnik, J.L., Knight, R.T. and Lee, R.R. (2004) Hemispheric asymmetries for kinematic and positional aspects of reaching. Brain, 127: 1145–1158.

Halsband, U., Schmitt, J., Weyers, M., Binkofski, F., Grützner, G. and Freund, H.-J. (2001) Recognition and imitation of pantomimed motor acts after unilateral parietal and premotor lesions: a perspective on apraxia. Neuropsychologia, 39: 200–216.

Hanna-Pladdy, B., Heilman, K.M. and Foundas, A.L. (2001) Cortical and subcortical contributions to ideomotor apraxia: analysis of task demands and error types. Brain, 124: 2513–2527.

Haruno, M., Wolpert, D.M. and Kawato, M. (2001) MOSAIC model for sensorimotor learning and control. Neural Comput., 13: 2201–2220.

Heath, M., Roy, E.A., Black, S.E. and Westwood, D.A. (2001) Intransitive limb gestures and apraxia following unilateral stroke. J. Clin. Exp. Neuropsychol., 23(5): 628–642.

Heilman, K.M. (1973) Ideational apraxia — a re-definition. Brain, 96: 861–864.

Heilman, K.M., Maher, L.M., Greenwald, M.L. and Rothi, L.J. (1997) Conceptual apraxia from lateralized lesions. Neurology, 49(2): 457–464.

Heilman, K.M. and Rothi, L.J. (1993) Apraxia. In: Heilman K.M. and Valenstein E. (Eds.), Clinical Neuropsychology (3rd ed.). Oxford University Press, New York, pp. 141–163.

Heilman, K.M., Rothi, L.G., Mack, L., Feinberg, T. and Watson, R.T. (1986) Apraxia after a superior parietal lesion. Cortex, 22(1): 141–150.

Heilman, K.M., Rothi, L.J. and Valenstein, E. (1982) Two forms of ideomotor apraxia. Neurology, 32: 342–346.

Heilman, K.M., Schwartz, H.D. and Geschwind, N. (1975) Defective motor learning in ideomotor apraxia. Neurology, 25(11): 1018–1020.

Helms Tillery, S.I., Soechting, J.F. and Ebner, T.J. (1996) Somatosensory cortical activity in relation to arm posture: nonuniform spatial tuning. J. Neurophysiol., 76(4): 2423–2438.

Hermsdörfer, J., Blankenfeld, H. and Goldenberg, G. (2003) The dependence of ipsilesional aiming deficits on task demands, lesioned hemisphere, and apraxia. Neuropsychologia, 41: 1628–1643.

Hermsdörfer, J., Goldenberg, G., Wachsmuth, C., Conrad, B., Ceballos-Baumann, A.O., Bartenstein, P., Schwaiger, M. and Boecker, H. (2001) Cortical correlates of gesture processing: clues to the cerebral mechanisms underlying apraxia during the imitation of meaningless gestures. Neuroimage, 14: 149–161.

Hermsdörfer, J., Hentze, S. and Goldenberg, G. (2006) Spatial and kinematic features of apraxic movement depend on the mode of execution. Neuropsychologia, 44: 1642–1652.

Hermsdörfer, J., Mai, N., Spatt, J., Marquardt, C., Veltkamp, R. and Goldenberg, G. (1996) Kinematic analysis of movement imitation in apraxia. Brain, 119: 1575–1586.

Hersch, M. and Billard, A.G. (2006) A biologically-inspired model of reaching movements. In Proceedings of the 2006 IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, pp. 1067–1072.

Ietswaart, M., Carey, D.P. and Della Sala, S. (2006) Tapping, grasping and aiming in ideomotor apraxia. Neuropsychologia, 44: 1175–1184.

Ietswaart, M., Carey, D.P., Della Sala, S. and Dijkhuizen, R.S. (2001) Memory-driven movements in limb apraxia: is there evidence for impaired communication between the dorsal and the ventral streams? Neuropsychologia, 39: 950–961.

Iriki, A., Tanaka, M. and Iwamura, Y. (1996) Coding of modified body schema during tool use by macaque postcentral neurons. Neuroreport, 7: 2325–2330.

Jacobs, D.H., Adair, J.C., Macauley, B., Gold, M., Gonzalez Rothi, L.J. and Heilman, K.M. (1999) Apraxia in corticobasal degeneration. Brain Cogn., 40: 336–354.

Jeannerod, M., Arbib, M., Rizzolatti, G. and Sakata, H. (1995) Grasping objects: the cortical mechanisms of visuomotor transformation. Trends Neurosci., 18: 314–320.

Jeannerod, M. and Decety, J. (1995) Mental motor imagery: a window into the representational stages of action. Curr. Opin. Neurobiol., 5: 727–732.

Johnson-Frey, S.H., Newman-Norlund, R. and Grafton, S.T. (2005) A distributed left hemisphere network active during planning of everyday tool use skills. Cereb. Cortex, 15: 681–695.

Kalaska, J.F., Scott, S.H., Cisek, P. and Sergio, L.E. (1997) Cortical control of reaching movements. Curr. Opin. Neurobiol., 7: 849–859.

Kertesz, A. and Ferro, J.M. (1984) Lesion size and location in ideomotor apraxia. Brain, 107: 921–933.

Kertesz, A. and Hooper, P. (1982) Praxis and language: the extent and variety of apraxia in aphasia. Neuropsychologia, 20(3): 275–286.

Kertzman, C., Schwarz, U., Zeffiro, T.A. and Hallett, M. (1997) The role of posterior parietal cortex in visually guided reaching movements in humans. Exp. Brain. Res., 114: 170–183.

Kohonen, T. (2001) Self-Organizing Maps. 3rd ed., Springer Series in Information Sciences. Vol. 30. Springer, Berlin.

Koski, L., Iacoboni, M. and Mazziotta, J.C. (2002) Deconstructing apraxia: understanding disorders of intentional movement after stroke. Curr. Opin. Neurol., 15: 71–77.

Krakauer, J.W., Ghilardi, M.-F. and Ghez, C. (1999) Independent learning of internal models for kinematic and dynamic control of reaching. Nat. Neurosci., 2(11): 1026–1031.

Krams, M., Rushworth, M.F., Deiber, M.-P., Frackowiak, R.S. and Passingham, R.E. (1998) The preparation, execution and suppression of copied movements in the human brain. Exp. Brain Res., 120(3): 386–398.

Laeng, B. (2006) Constructional apraxia after left or right unilateral stroke. Neuropsychologia, 44(9): 1595–1606.

Lausberg, H. and Cruz, R.F. (2004) Hemispheric specialisation for imitation of hand-head positions and finger configurations: a controlled study in patients with complete callosotomy. Neuropsychologia, 42: 320–334.

Lausberg, H., Cruz, R.F., Kita, S., Zaidel, E. and Ptito, A. (2003) Pantomime to visual presentation of objects: left hand dyspraxia in patients with complete callosotomy. Brain, 126: 343–360.

Lausberg, H., Davis, M. and Rothenhäusler, A. (2000) Hemispheric specialization in spontaneous gesticulation in a patient with callosal disconnection. Neuropsychologia, 38: 1654–1663.

Lausberg, H., Göttert, R., Münssinger, U., Boegner, F. and Marx, P. (1999) Callosal disconnection syndrome in a left-handed patient due to infarction of the total length of the corpus callosum. Neuropsychologia, 37: 253–265.

Lee, D.N., Craig, C.M. and Grealy, M.A. (1999) Sensory and intrinsic coordination of movement. Proc. R. Soc. Lond. B, 266: 2029–2035.

Lehmkuhl, G., Poeck, K. and Willmes, K. (1983) Ideomotor apraxia and aphasia: an examination of types and manifestations of apraxic symptoms. Neuropsychologia, 21(3): 199–212.

Leiguarda, R. (2001) Limb apraxia: cortical or subcortical. Neuroimage, 14: S137–S141.

Leiguarda, R.C. and Marsden, C.D. (2000) Limb apraxias: higher order disorders of sensorimotor integration. Brain, 123: 860–879.

Maravita, A., Spence, C. and Driver, J. (2003) Multisensory integration and the body schema: close to hand and within reach. Curr. Biol., 13: R531–R539.

Marchetti, C. and Sala, S.D. (1997) On crossed apraxia. Description of a right-handed apraxic patient with right supplementary motor area damage. Cortex, 33(2): 341–354.

Matelli, M. and Luppino, G. (2001) Parietofrontal circuits for action and space perception in the macaque monkey. Neuroimage, 14: S27–S32.

Merians, A.S., Clark, M., Poizner, H., Jacobs, D.H., Adair, J.C., Macauley, B., Rothi, L.J.G. and Heilman, K.M. (1999) Apraxia differs in corticobasal degeneration and left-parietal stroke: a case study. Brain Cogn., 40: 314–335.

Merians, A.S., Clark, M., Poizner, H., Macauley, B., Gonzalez Rothi, L.J. and Heilman, K.M. (1997) Visual-imitative dissociation apraxia. Neuropsychologia, 35(11): 1483–1490.

Moll, J., de Oliveira-Souza, R., Passman, L.J., Souza-Lima, F. and Andreiuolo, P.A. (2000) Functional MRI correlates of real and imagined tool-use pantomime. Neurology, 54: 1331–1336.

Morasso, P. (1981) Spatial control of arm movements. Exp. Brain Res., 42: 223–227.

Mühlau, M., Hermsdörfer, J., Goldenberg, G., Wohlschläger, A.M., Castrop, F., Stahl, R., Röttinger, M., Erhard, P., Haslinger, B., Ceballos-Baumann, A.O., Conrad, B. and Boecker, H. (2005) Left inferior parietal dominance in gesture imitation: an fMRI study. Neuropsychologia, 43: 1086–1098.

Nehaniv, C.L. and Dautenhahn, K. (2002) The correspondence problem. In: Dautenhahn K. and Nehaniv C.L. (Eds.), Imitation in Animals and Artifacts. MIT Press, London, pp. 41–61.

Ochipa, C., Rothi, L.J.G. and Heilman, K.M. (1992) Conceptual apraxia in Alzheimer's disease. Brain, 115: 1061–1071.

Ochipa, C., Rothi, L.J.G. and Heilman, K.M. (1994) Conduction apraxia. J. Neurol. Neurosurg. Psychiatry, 57: 1241–1244.

Orban, G.A., Van Essen, D. and Vanduffel, W. (2004) Comparative mapping of higher visual areas in monkeys and humans. Trends Cogn. Sci., 8(7): 315–324.

Oztop, E. and Arbib, M.A. (2002) Schema design and implementation of the grasp-related mirror neuron system. Biol. Cybern., 78: 116–140.

Papagno, C., Della Sala, S. and Basso, A. (1993) Ideomotor apraxia without aphasia and aphasia without apraxia: the anatomical support for a double dissociation. J. Neurol. Neurosurg. Psychiatry, 56: 286–289.

Parakh, R., Roy, E., Koo, E. and Black, S. (2004) Pantomime and imitation of limb gestures in relation to the severity of Alzheimer's disease. Brain Cogn., 55: 272–274.

Peigneux, P., Van der Linden, M., Garraux, G., Laureys, S., Degueldre, C., Aerts, J., Del Fiore, G., Moonen, G., Luxen, A. and Salmon, E. (2004) Imaging a cognitive model of apraxia: the neural substrate of gesture-specific cognitive processes. Hum. Brain Mapp., 21: 119–142.

Peigneux, P., Salmon, E., Van der Linden, M., Garraux, G., Aerts, J., Delfiore, G., Deguel-dre, C., Luxen, A., Orban, G. and Franck, G. (2000) The role of lateral occipi-totemporal junction and area MT/V5 in the visual analysis of upper-limb postures. Neuroimage, 11: 644–655.

Petreska, B. and Billard, A.G. (2006) A neurocomputational model of an imitation deficit following brain lesion, in Proceedings of 16th International Conference on Artificial Neural Networks (ICANN 2006). Lecture Notes in Computer Science, LNCS 4131: 770–779.

Platt, M.L. and Glimcher, P.W. (1998) Response fields of intraparietal neurons quantified with multiple saccadic targets. Exp. Brain Res., 121: 65–75.

Platz, T. and Mauritz, K.-H. (1995) Human motor planning, motor programming, and use of new task-relevant information with different apraxic syndromes. Eur. J. Neurosci., 7: 1536–1547.

Poeck, K. (1983) Ideational apraxia. J. Neurol., 230: 1–5.

Poizner, H., Clark, M.A., Merians, A.S., Macauley, B., Rothi, L.J.G. and Heilman, K.M. (1995) Joint coordination deficits in limb apraxia. Brain, 118: 227–242.

Poizner, H., Mack, L., Verfaellie, M., Rothi, L.J.G. and Heilman, K.M. (1990) Three-dimensional computergraphic analysis of apraxia. Neural representations of learned movement. Brain, 113(1): 85–101.

Poizner, H., Merians, A.S., Clark, M.A., Rothi, L.J.G. and Heilman, K.M. (1997) Kinematic approaches to the study of apraxic disorders. In: Rothi L.J.G. and Heilman K.M. (Eds.), Apraxia: The neuropsychology of Action. Psychology Press, Hove, UK, pp. 93–109.

Pramstaller, P.P. and Marsden, C.D. (1996) The basal ganglia and apraxia. Brain, 119: 319–340.

Raos, V., Umiltá, M.-A., Gallese, V. and Fogassi, L. (2004) Functional properties of grasping-related neurons in the dorsal premotor area F2 of the macaque monkey. J. Neurophysiol., 92: 1990–2002.

Rapcsak, S.Z., Ochipa, C., Anderson, K.C. and Poizner, H. (1995) Progressive ideomotor apraxia: evidence for a selective impairment of the action production system. Brain Cogn., 27: 213–236.

Raymer, A.M., Maher, L.M., Foundas, A.L., Heilman, K.M. and Rothi, L.J.G. (1997) The significance of body part as tool errors in limb apraxia. Brain Cogn., 34: 287–292.

Raymer, A.M., Merians, A.S., Adair, J.C., Schwartz, R.L., Williamson, D.J.G., Rothi, L.J.G., Poizner, H. and Heilman, K.M. (1999) Crossed apraxia: Implications for handedness. Cortex, 35(2): 183–199.

Rizzolatti, G. and Arbib, M.A. (1998) Language within our grasp. Trends Neurosci., 21(5): 188–194.

Rizzolatti, G. and Craighero, L. (2004) The mirror-neuron system. Annu. Rev. Neurosci., 27: 169–192.

Rizzolatti, G., Fogassi, L. and Gallese, V. (2002) Motor and cognitive functions of the ventral premotor cortex. Curr. Opin. Neurobiol., 12: 149–154.

Rizzolatti, G. and Luppino, G. (2001) The cortical motor system. Neuron, 31: 889–901.

Rothi, L.J.G. and Heilman, K.M. (1984) Acquisition and retention of gestures by apraxic patients. Brain Cogn., 3(4): 426–437.

Rothi, L.J.G., Ochipa, C. and Heilman, K.M. (1991) A cognitive neuropsychological model of limb praxis. Cogn. Neuropsychol., 8(6): 443–458.

Rothi, L.J.G., Ochipa, C. and Heilman, K.M. (1997) A cognitive neuropsychological model of limb praxis and apraxia. In: Rothi L.J.G. and Heilman K.M. (Eds.), Apraxia: The neuropsychology of Action. Psychology Press, Hove, UK, pp. 29–49.

Roy, E.A., Black, S.E., Winchester, T.R. and Barbour, K.L. (1992) Gestural imitation following stroke. Brain Cogn., 30(3): 343–346.

Roy, E.A., Heath, M., Westwood, D., Schweizer, T.A., Dixon, M.J., Black, S.E., Kalbfleisch, L., Barbour, K. and Square, P.A. (2000) Task demands and limb apraxia in stroke. Brain Cogn., 44: 253–279.

Roy, E.A., Square, P.A. (1985) Common considerations in the study of limb, verbal and oral apraxia. In: Roy, E.A. (Ed.), Neuropsychological Studies of Apraxia and Related Disorders. North-Holland, Amsterdam, Series Advances in Psychology, Vol. 23, pp. 111–161.

Ruby, P., Sirigu, A. and Decety, J. (2002) Distinct areas in parietal cortex involved in long-term and short-term action planning: a PET investigation. Cortex, 38: 321–339.

Rumiati, R.I., Weiss, P.H., Shallice, T., Ottoboni, G., Noth, J., Zilles, K. and Fink, G.R. (2004) Neural basis of pantomiming the use of visually presented objects. Neuroimage, 21(4): 1224–1231.

Salter, J.E., Roy, E.A., Black, S.E., Joshi, A. and Almeida, Q.J. (2004) Gestural imitation and limb apraxia in corticobasal degeneration. Brain Cogn., 55(2): 400–402.

Sauser, E.L. and Billard, A.G. (2006) Parallel and distributed neural models of the ideomotor principle: an investigation of imitative cortical pathways. Neural Netw., 19(3): 285–298.

Schaal, S. and Schweighofer, N. (2005) Computational motor control in humans and robots. Curr. Opin. Neurobiol., 6: 675–682.

Schnider, A., Hanlon, R.E., Alexander, D.N. and Benson, D.F. (1997) Ideomotor apraxia: behavioral dimensions and neuroanatomical basis. Brain Lang., 57: 125–136.

Scholz, J.P. and Schöner, G. (1999) The uncontrolled manifold concept: identifying control variables for a functional task. Exp. Brain Res., 126(3): 289–306.

Scott, S.H., Sergio, L.E. and Kalaska, J.F. (1997) Reaching movements with similar handpaths but different arm orientations. II. Activity of individual cells in dorsal premotor cortex and parietal area 5. J. Neurophysiol., 78: 2413–2416.

Sereno, M.I. and Tootell, R.B. (2005) From monkeys to humans: what do we now know about brain homologies? Curr. Opin. Neurobiol., 15(2): 135–144.

Simon, O., Mangin, J.-F., Cohen, L., Le Bihan, D. and Dehaene, S. (2002) Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. Neuron, 33(3): 475–487.

Sirigu, A., Daprati, E., Pradat-Diehl, P., Franck, N. and Jeannerod, M. (1999) Perception of self-generated movement following left parietal lesion. Brain, 122: 1867–1874.

Todorov, E. and Jordan, M.I. (2002) Optimal feedback control as a theory of motor coordination. Nat. Neurosci., 5(11): 1226–1235.

Uno, Y., Kawato, M. and Suzuki, R. (1989) Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model. Biol. Cybern., 61: 89–101.

Vindras, P., Desmurget, M. and Viviani, P. (2005) Error parsing in visuomotor pointing reveals independent processing of amplitude and direction. J. Neurophysiol., 94: 1212–1224.

Watson, R.T., Fleet, W.S., Rothi, L.J.G. and Heilman, K.M. (1986) Apraxia and the supplementary motor area. Arch. Neurol., 43(8): 787–792.

Watson, R.T. and Heilman, K.M. (1983) Callosal apraxia. Brain, 106: 391–403.

Weiss, P.H., Dohle, C., Binkofski, F., Schnitzler, A., Freund, H.-J. and Hefter, H. (2001) Motor impairment in patients with parietal lesions: disturbances of meaningless arm movement sequences. Neuropsychologia, 39: 397–405.

Wise, S.P., Boussaoud, D., Johnson, P.B. and Caminiti, R. (1997) Premotor and parietal cortex: corticocortical connectivity and combinatorial computations. Annu. Rev. Neurosci., 20: 25–42.

Wolpert, D.M. and Ghahramani, Z. (2000) Computational principles of movement neuroscience. Nat. Neurosci., 3: 1212–1217.

Wolpert, D.M., Ghahramani, Z. and Flanagan, J.R. (2001) Perspectives and problems in motor learning. Trends Cogn. Sci., 5(11): 487–494.