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How we interact with objects: learning from brain lesions

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Motor deficits are the most common outcome of brain damage. Although a large part of such disturbances arises from loss of elementary sensorimotor functions, several syndromes cannot be explained purely on these bases. In this article, we briefly describe higher-order motor impairments, with specific attention to the characteristic ability of the human hand to interact with objects and tools. Disruption of this motor skill at several independent levels is used to outline a comprehensive model, in which various current proposals for a modular organization of hand–object interactions can be integrated. In this model, cortical mechanisms related to object interaction are independent from representations of the semantic features of objects.

Introduction

Hand–object interactions take multiple forms. An object can be picked up with the intention of moving it to a new location, or handing it to another person. It can be explored or manipulated; it can be described, or used as a tool. Opposition of the thumb is a common feature in most such actions, yet placement of the fingers and amplitude of their aperture vary considerably according to the type of hand–object interaction, as do orientation of the wrist and forearm while reaching for the target. The mechanisms involved in the process of grasping and those related to tool use have been extensively described (for reviews see [1,2]). Taken together, these descriptions suggest a modular organization of the action system. In this article, we review recent data from neuropsychology showing that, depending on the goal attained, separate sets of incoming information are selected, and different forms of stored knowledge are recalled. We will relate these findings to observations in the domain of neurophysiology, suggesting that separate goals recruit separate neural systems. On these bases, we will attempt to provide a comprehensive model of how different types of hand–object interactions are segregated in the brain.

Reaching for an object in space

Grasping is a very much studied action. Although apparently simple, successful grasping requires a series of computations devoted to localizing the target in space, analyzing its dimensions, shape and orientation, and selecting the proper hand configuration. This complex mechanism can operate independently from object identification. The neuropsychological literature provides consistent evidence that visuomotor transformation can be severely disrupted, in spite of preserved recognition. This is the case for optic ataxia, a condition that follows lesions to the superior parietal lobule [3] and is characterized by awkward and poorly functional grasping of simple neutral objects (cubes, cylinders) [4,5]. Several studies support the hypothesis that the core deficit in ataxia is visuomotor, rather than purely perceptual. Indeed, if not actually required to grasp the object, ataxic patients can often demonstrate the target's size by appropriately scaling the aperture of their fingers; furthermore, optic ataxia frequently affects only one hand, and can be modulated by the target's location [6], which rules out a purely perceptual origin. Interestingly, severe hand-shaping disturbances can persist even when the patient correctly localizes the object [4,7], suggesting that locating a visual target in space and grasping it might rely on separate processes, both of which are independent from those involved in object identification.

This latter aspect clearly emerges when one considers cases of visual agnosia, a pervasive disorder in object recognition, which typically follows lesions to the temporal lobe, and ventrolateral occipital cortex (often bilaterally) [8]. The most extensively studied case is patient D.F. [9], whose major symptom was a complete inability to describe the shape, size and orientation of visually presented objects. Despite these compromised recognition processes, D.F.'s visuomotor abilities were unaffected, and she could correctly grasp objects, or properly position her hand to insert it into an oriented slot.

In recent years, several experiments have revealed an interesting aspect of both optic ataxia and visual agnosia. Although object identification is not required for grasping, knowledge of what the target is helps ataxic patients to reach accurately for it. Familiar objects elicit more accurate grasping than neutral objects [5] and the introduction of a delay before the movement improves performance (presumably because patients can use a stored representation of the target) [10,11]. This is not the case for visual agnosia, in which even short delays significantly compromise grasping abilities [12]. These observations led to the hypothesis that the disruption occurring in optic ataxia might affect only immediate

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visuomotor control, and more particularly hand shaping [6]. Conversely, 'on-line' visuo-motor transformations are preserved in visual agnosia.

Two visual streams: more than a simple dichotomy?

The situation presented by optic ataxia and visual agnosia has long been considered an example of double dissociation (see Box 1), although this statement has recently been questioned [6]. Nevertheless, the differential impairment found in these two syndromes strongly supports the hypothesis that when a visual target is presented, information is likely to follow one of two main pathways according to the goal, which might be locating the target in space, picking it up or identifying it [13].

From the functional-anatomical perspective, the lesions responsible for visual agnosia and optic ataxia are neatly aligned along two separate neural streams ('ventral' or occipito-temporal, and 'dorsal' or occipito-parietal), both originating from early visual areas [13–15]. In recent years, a pure dichotomy that segregates perception and action has been questioned. Experiments with healthy subjects largely used visual illusions to dissociate perceptual and motor responses, which are now receiving interesting alternative explanations [16,17]. Similarly, the differential behaviour of patients in immediate (on-line) versus delayed conditions suggest that the picture is more complex than initially claimed. Mutual connections between dorsal and ventral structures have gradually been discovered [18–21], and both streams are no longer considered unitary structures (for reviews see [6,22]).

In the monkey's dorsal pathway, separate outputs are described running from a crucial region in early visual areas to separate areas of the posterior parietal cortex. One output, from area V6, projects to the superior parietal lobule (SPL), whereas the other, from area MT/V5, has more connections to the inferior parietal lobule (IPL) [22]. These two parietal areas are further connected to separate frontal regions, the more dorsal pathway ('dorso-dorsal stream') running from SPL to the dorsal premotor cortex (area F2, [23]), the more ventral system ('ventro-dorsal stream') projecting from IPL to ventral premotor cortex (i.e. areas F4 and F5, [23]), and prefrontal areas. In the monkey brain, these regions are closely related, not only to space computation, but also to grasping and manipulation. If a comparable segregation exists in humans, a clear subdivision could be claimed between a dorso-dorsal pathway devoted to on-line conversion of target location into the proper reaching gesture and a more ventral stream devoted to transforming objects features in the appropriate hand actions [22]. Neuropsychological findings support this view [4,9].

Box 1. Single cases and dissociations

The term dissociation applies when one patient (or a group of patients) exhibits differential performances in two separate experimental tasks. We speak of double dissociation (DD) if a second patient (or group) shows the opposite pattern in the same set of tasks. In other words, if we administer task A and B to two patients with lesions *X* and *Y*, respectively, a (single) dissociation occurs if the patient with lesion *X* fails in task A and not B, but a DD occurs if, in addition, the patient with lesion *Y* fails in task B but not A. On these bases, it is generally inferred that there exists a cognitive process A′ that is required in task A (and is selectively affected by lesion *X*), which is not required in task B. Similarly, we assume that a second cognitive process B′ is selectively required in task B (and is affected by lesion *Y*), but is not involved in task A.

Before the advent of neuroimaging, dissociations were extensively used as a tool to localize mental functions in the brain. As recently noted by more than one author [49–51], the study of dissociation has its limitations, the most relevant being related to the assumptions made. To claim a DD, we assume that damage affecting each patient is selective, that is, it involves only one of the neural modules supporting the tasks. Second, we assume that each task is equally selective. Neither condition is easily assessed [52], which limits the degree to which we can generalize. However, this type of study can still represent a powerful addition to the domain of neuroimaging research, as lesion studies can isolate which part of the network identified by neuroimaging is necessary to perform a given task.

Grasping an object and using an object: separate modules for separate goals

In daily life, we make a difference when grasping a pair of scissors to put them in the kitchen drawer, or when reaching for them to cut a sheet of paper. In the former action the brain mainly relies on the object's basic features (i.e. shape or size), but in the latter it also needs to know how this particular tool is operated, if multi-step actions are required or accurate posture transitions should be planned. Evidence from neuropsychology suggests that this second set of activities can be selectively impaired. One example comes from patients like L.L., whose core deficit was a severe impairment in producing the appropriate hand shaping when *using* an object. Her elementary sensory and motor functions were otherwise unimpaired, as was the ability to recognize and name the presented tools.

In contrast with cases of optic ataxia [4,5], patients like L.L. can adequately reach for a visual target, properly scaling the fingers to match its shape and size [24,25], but then fail to use the grasped object correctly. Similarly, they are often unable to pantomime the corresponding action (Figure 1), or select the appropriate hand configuration for using a tool. This particular deficit meets the definition of apraxia, as first proposed by Liepmann in the 19th century (see [26] for a review) (Box 2). Apraxia is commonly related to extensive damage to the posterior left hemisphere, typically involving the IPL. At present, several varieties of apraxia are described [27], and patients show dissociations [24,28–30] that point to a certain degree of modularity within the praxic system. In particular, cases like L.L.'s suggest that the neural system devoted to hand pre-shaping when grasping with the intention to *move* a tool (as was described in the previous section) might function independently from that responsible for hand pre-shaping when grasping to *use* the same object [31].

Skilful tool use requires both acquisition of the specific motor routines for a particular goal, and the ability to retrieve this competence in response to the proper perceptual trigger [32–36]. The latter aspect is linked to sensitivity to both low-level (i.e. geometry), and high-level object 'affordances' (i.e. mechanical properties), which might directly activate the motor schemas responsible for

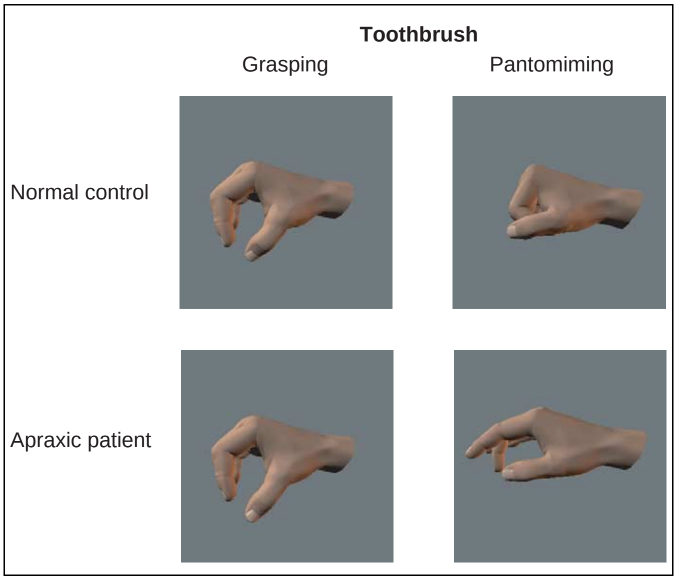

Figure 1. Object use in apraxia. Hand postures generated for a visually presented object (toothbrush) by one control subject and one apraxic patient (L.L.) with bilateral inferior parietal lobe lesions, under two different instructions ('reach and move', left; and 'pantomime the use', right). Each hand posture was obtained by recording angular variations of the different hand joints (metacarpal-phalangeal, proximal and distal interphalangeal, abduction between adjacent fingers and thumb rotation) by means of an instrumented glove (with 22 motion sensors; Cyber Glove™, Virtual Technologies). Note that the unlike the normal control the apraxic subject is unable to generate the hand posture adopted during the use of the toothbrush, even though hand shaping recorded during reaching for the same object was intact.

functional interactions [37–39]. Studies in experimental psychology support the notion that visual presentation of an object facilitates preparation of actions congruent with the objects' geometrical properties. This 'visuomotor priming' effect [40] endorses the possibility that comparable stored representations might also exist for complex hand–object interactions.

Neuroimaging studies have shown consistent activations in the left posterior parietal cortex when volunteers retrieve knowledge about hand and finger movements related to tool use [34,41]. This result is in agreement with neuropsychological reports that lesions within this area produce difficulties in actual, or more often pantomimed, tool use [27]. Interestingly, diffusion tensor magnetic resonance imaging studies have shown that within the arcuate fasciculus an anterior segment directly connects the inferior parietal cortex to Broca's area, and a posterior segment links the inferior parietal region with the temporal cortex [18,19]. These connections could constitute an ideal network for integrating functional properties of tools into the complex movement patterns supporting object use. Results from patients further suggest that this cortical circuitry might involve storage units that are specific to the complex manual configurations directly associated with the use of tools [24,25].

Object semantic knowledge

Knowledge about an object's use is a broad concept. It means being able to report (i) what the object is used for and how it is operated, (ii) the context in which it is used, and (iii) how the hand and fingers should be positioned when directly interacting with it. Recent reports suggest that these different forms of stored knowledge might be segregated [42]. Object use can be impaired despite intact semantic knowledge, as shown in the previous section [24,36,43,44], but the opposite can also occur [45,46]. An example of the latter deficit is that in patient F.B., who suffered bilateral inferior temporal lobe lesions [46]. Unlike D.F. [9], whose defect was selective for the visual modality, F.B. showed a pervasive deficit in recognizing objects, which he could neither name nor describe their

Box 2. Motor representations in apraxia

Clinicians explore limb praxis by requiring patients to produce a gesture on imitation or verbal command, or by asking them to use tools or pantomime the corresponding action. However, overt behavioural deficits seem to be only one part of the story. In most cases, apraxia also affects the ability to simulate movements, supporting the hypothesis that mental representations of gestures and hand–object interactions are primarily affected. The representative features of apraxia clearly emerge when patients are required to access motor mental images [24] (see Figure I) or to overtly monitor self-generated actions. With regard to the latter, Sirigu and colleagues [57] asked apraxic patients to execute progressively complex gestures in an ambiguous setting, and decide whether the visible moving hand belonged to them. Normal subjects are reasonably accurate in solving this task [58]. By contrast, apraxic patients failed to retrieve their own motor productions, and misattributed gestures of a healthy actor to themselves [57]. This result is particularly striking given that the gestures produced by apraxics were noticeably clumsy compared with those of the actor, thus creating a clear mismatch that should have easily disambiguated the setting. Proprioceptive information being preserved in these patients, apraxic impairment is better ascribed to a more specific difficulty in either generating or continuously updating an internal representation of their gestures, which appears to confirm the existence of a powerful representative component to the disorder.

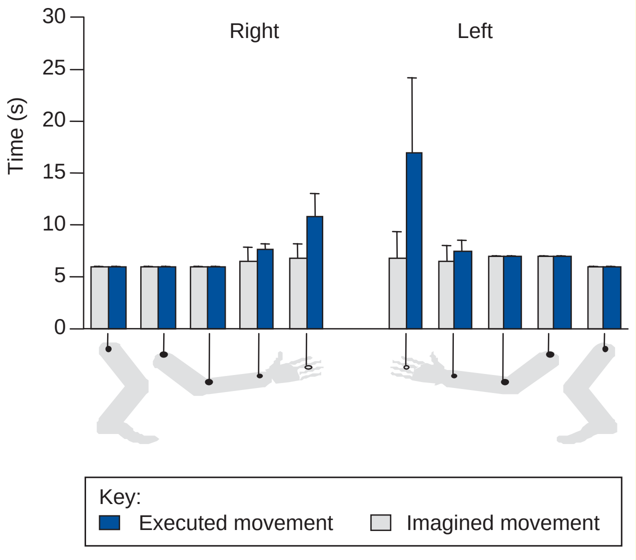

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Figure I. Motor representations in apraxia. Patient L.L [24] was required to mentally simulate movements of the upper and lower limb (grey bars). Subsequently, actual execution of each movement was required, following the same protocol (blue bars). Previous mental chronometry studies [65,66] have shown that in healthy controls duration of the simulated movements mimics that of the real movement. By contrast, the patient showed a significant decoupling between real and mentally simulated movements, which emerged selectively for the upper limb. This result suggests that the patient either failed to generate, or to monitor, her internal motor representation.

Box 3. Cerebral localization of functions

Hemispheric specialization and intrahemispheric localization of single functions has long been an issue in neuropsychology and cognitive neuroscience (for a review see [53]). Recently, new techniques such as functional neuroimaging and transcranial magnetic stimulation have challenged previous theories, requiring the re-interpretation of many brain functions as based on larger networks than originally claimed [54]. Hand–object interactions might be one such case. In Liepmann's original description [26], praxis functions were viewed as a selective competence of the left hemisphere, mainly based on posterior areas such as the parietal cortex. Recent observations have shown that right hemisphere lesions can affect performance of naturalistic actions [33] and imitation [55] to a comparable extent. One reason why right-brain damaged (RBD) patients should fail in naturalistic actions is the multi-step nature of many daily-life activities, which conceivably taps into an already damaged attentional system [33,56]. Similarly, RBD patients fail in imitating gestures when perceptual demands rise [55], suggesting that a single brain structure is not likely to be in charge for the whole process. In other words, the majority of the cortex might become involved according to the cognitive demands of the task [33,55,56]. It is intuitive to see how moving towards a network view could accommodate unusual cases as the occurrence of severe deficits arising from otherwise small brain lesions. This might be the case for lesions to areas that have relatively unspecialized functions but contribute to the functioning of a larger network.

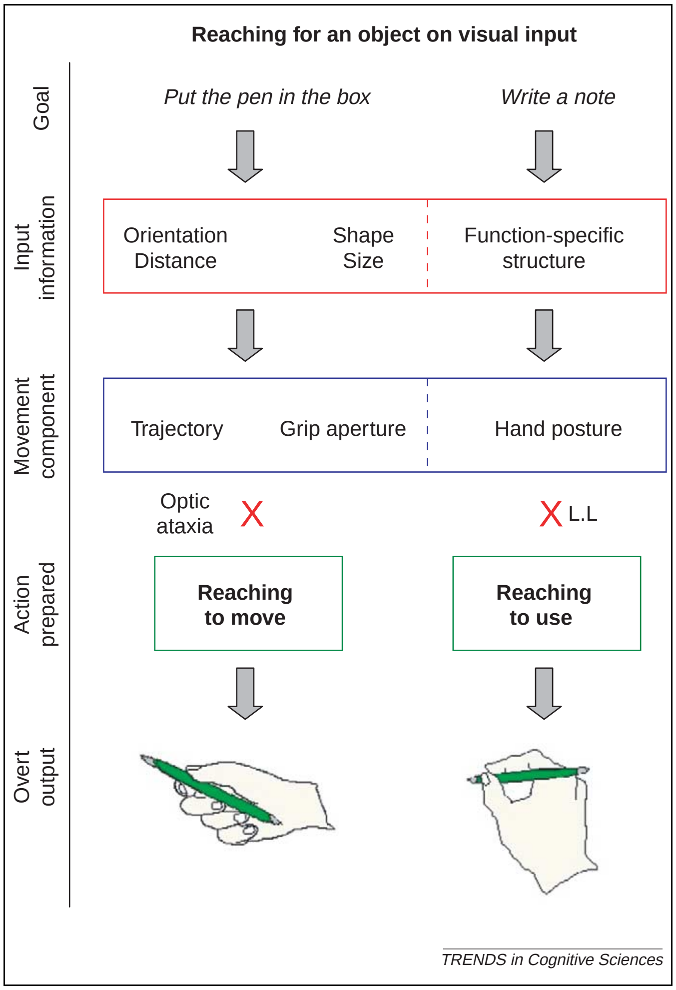

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Figure 2. Parallel pathways for hand–object interactions. A schematic model showing the two separate coordinate pathways involved in object-related gestures. According to the goal to be achieved, different sets of visual information become relevant in preparing the required hand movement. This modular organization is supported by the differential performance of patients with optic ataxia (impaired when reaching to *move* an object), and patient L.L. [24] (impaired only when reaching to *use* an object). Patients D.F. [9] and F.B. [46] (as described in the text) were not severely impaired when dealing with these tasks; D.F. could properly describe the object when allowed to use the tactile rather than the visual modality. Similarly, F.B. could report and demonstrate the correct hand posture for using the object, although he was unaware of its final goal.

function. However, he could precisely produce the movements involved in purposeful manipulation of the presented tool. For example, when asked to identify a nail clipper, F.B. could skilfully manipulate its movable parts and describe his movements, but defined the object function as: ‘it might be used to attach things together’ [46]. Similar behaviour has been described in patients suffering from semantic dementia [47], although in this case contrasting evidence has also been reported [35,48].

How can tools be properly manipulated when relevant semantic information about them is lost? One possibility is that a functional dissociation exists between knowledge of the object's semantic properties (including overt knowledge of an object's function), and the ability to interact with it. In this view, a mechanism based on the object's affordances could directly trigger the proper hand–object interaction, with no need for semantic knowledge on the object's use [46]. Alternatively, adequate tool use might rely on other factors, such as familiarity, residual conceptual knowledge, and the ability to use affordances, and/or engage in mechanical problem solving to derive function [35]. This intriguing debate, which impinges on the broader concept of a single versus separate semantic systems, leads to more complex issues of localization of function and whether (and how) separate modules can be isolated in the brain, or a more holistic network advocated instead (Box 3).

Hand–object interactions: separate routes in the brain

The observations reported in the previous sections suggest the existence of separate routes in the brain devoted to hand–object interactions. We suggest that the neural distribution and recruitment of these systems would largely depend on the goal to be achieved. Let us consider the simple example of a familiar object being presented (Figure 2). Two major sources of information are available: one derived from the visual input, the other from stored knowledge on the target. The first source provides information on the object's ‘intrinsic’ (i.e. shape and size) and ‘extrinsic’ (i.e. orientation and location) properties. Moreover, it makes the object's affordances available (i.e. geometry and mechanical properties), and can guide the choice for the best posture. When novel objects are presented, this source of information is likely to be the more relevant. If the action goal is moving the object to a new location, conceptual knowledge is not required and the activity of areas located within the superior parietal region probably suffice (the ‘reaching to move’ pathway). Being based on moment-to-moment information about the target, this system works extremely fast and allows accurate on-line correction during the movement itself. Similarly, it is ideal for dealing with novel or neutral stimuli, for which semantic stored knowledge is not available, and can support grasping when stored knowledge is lost (as in visual agnosia [9]). Lesions of this pathway result in misreaching and poor hand-shaping when dealing with *immediate* visuomotor actions, particularly if directed to novel or unfamiliar targets. This is the case for optic ataxia [4,5].

When more specific actions are required, that is, when we wish to *use* an object, other information is recruited (the 'reaching to use' pathway). Perceptual affordances can guide the correct hand posture, but only functional knowledge of object properties permits accurate purposeful gestures. Integration of stored knowledge is crucial in the production of complex movements, and probably relies on structures in the inferior parietal cortex, which are relatively more aligned with the ventral visual pathway. These structures could provide an alternative source of information when the 'direct' pathway is damaged (as in optic ataxia patients dealing with familiar objects [4]). The object functional system can be further segregated to distinguish between semantic knowledge of an object and its mechanical properties (via affordance-based identification), as illustrated by patients L.L. [24] and F.B. [46]. Thus, the sensorimotor and semantic features of tools can be processed by relatively independent neural systems (Box 4).

In conclusion, we suggest the existence of separate cortical mechanisms related to object interaction: one specialized for the representation of the hand postural schemata required during tool use, the other associated with fast on-line hand scaling in the context of reaching to move the object. We have examined evidence suggesting that these mechanisms operate independently in some circumstances (i.e. brain damage) and are disconnected from representations pertaining to the object semantic features. These findings have implications for how object knowledge is represented in the brain, and for the modular organization of cognitive functions.

Box 4. Motor attention and tool use

The term 'motor attention' describes attentional processes associated with arm and hand movements [59]. Paradigms used to study motor attention require subjects to prepare covertly for the execution of a hand movement in a given direction. Redirection of covert orienting is often required, by using invalid pre-cues that force the subject to prepare the movement towards a given location but later re-direct it to the proper target in a different location. Transcranic magnetic stimulation (TMS) transiently disrupts the functioning of the stimulated brain region (so in a sense simulating a lesion), with no risks to the participants. By applying TMS over the anterior parietal region the ability to redirect motor attention was transiently disrupted in healthy subjects [60], mimicking what occurs following a brain lesion in the same area [61]. It has been proposed that many of the symptoms presented by left parietal patients can be explained as a deficit in reorienting motor attention [59]. These patients are mostly impaired in tasks that require sequences of movements, or transitions between postures [62–64], that is, in activities requiring constant redirection of motor attention from one movement to the next. In tool use, updating of motor attention would be involved to a high degree, given that the body schema should be updated to accommodate the tool. Use of 'body parts as objects' is a common type of error in apraxic patients, and could be explained as a failure to update the body representation to include the tool.

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