Published in final edited form as:
Handb Clin Neurol. 2018 ; 151: 349–363. doi:10.1016/B978-0-444-63622-5.00017-6.

Limb apraxia and the left parietal lobe

LAUREL J. BUXBAUM[1,*], **JENNIFER RANDERATH**[2]

[1]Moss Rehabilitation Research Institute, Elkins Park, PA, United States

[2]Motor Cognition Group, Clinical Neuropsychology and Lurija Institute for Rehabilitation and Health Sciences, University of Konstanz, Konstanz; and Schmieder Foundation for Sciences and Research, Allensbach, Germany

Abstract

Limb apraxia is a heterogeneous disorder of skilled action and tool use that has long perplexed clinicians and researchers. It occurs after damage to various loci in a densely interconnected network of regions in the left temporal, parietal, and frontal lobes. Historically, a highly classificatory approach to the study of apraxia documented numerous patterns of performance related to two major apraxia subtypes: ideational and ideomotor apraxia. More recently, there have been advances in our understanding of the functional neuroanatomy and connectivity of the left-hemisphere "tool use network," and the patterns of performance that emerge from lesions to different loci within this network. This chapter focuses on the left inferior parietal lobe, and its role in tool and body representation, action prediction, and action selection, and how these functions relate to the deficits seen in patients with apraxia subsequent to parietal lesions. Finally, suggestions are offered for several future directions that will benefit the study of apraxia, including increased attention to research on rehabilitation of this disabling disorder.

INTRODUCTION

Limb apraxia is a heterogeneous disorder historically defined by exclusion: deficits in skilled movement not caused by weakness, deafferentation, abnormal tone or posture, tremors or chorea, intellectual deterioration, or poor comprehension. As a result, it has been difficult for clinicians and researchers to define exactly what apraxia *is*. Focusing primarily on limb apraxia after left parietal stroke, this chapter examines the neuroanatomic substrates of apraxia, and reviews historical accounts and recent research on the role of the parietal lobe in skilled action. Recent promising approaches to apraxia treatment are briefly considered. In conclusion,it is suggested that much past confusion can be reduced if limb apraxia is considered to consist of two major clusters of behaviors reflecting damage to representational and spatiotemporal components of skilled action, which may be attributed to damage to distinct loci in a distributed left-hemisphere network.

---

[*]Correspondence to: Laurel J. Buxbaum, MRRI, Medical Arts Building, 50 Township Line Road, Elkins Park PA 19127, United States. lbuxbaum@einstein.edu.

CLINICAL ASSESSMENT

In the past century, many types of apraxic deficits have been described (e.g., dressing apraxia, constructional apraxia, oral apraxia). Here we concentrate on apraxia of the limbs as observed in unilateral stroke populations.

Tests

Most limb apraxia test batteries developed in the 20th century include imitation of meaningful or meaningless actions, pantomime of object use without real objects being present, and demonstration of object use with only the tool in hand[1] (De Renzi et al., 1968; Rothi and Heilman, 1984; Poeck, 1986). Errors such as omissions, substitutions (e.g., stirring movement when hammering is asked for), perseverations, wrong grip postures, or incorrect end postures are scored. Little has changed in modern test batteries for apraxia (Power et al., 2010; Vanbellingen et al., 2010a, b), though some batteries additionally include assessment of gesture understanding (Kalenine et al., 2010).

Recently, several short screening tests have been developed that allow for rapid administration within 10 minutes on the ward (Vanbellingen etal., 2010a, b; Leiguarda etal., 2014; Weiss-Blankenhorn and Eschenbeck, 2014; Tessari et al., 2015). Despite the fact that the selection and application of actual tools may be affected in many apraxic patients (Buxbaum, 1998), few test batteries include this component (Goodglass and Kaplan, 1972). One reason for this may be that many apraxic patients appear less impaired in structured contexts such as test situations (Randerath et al., 2011). The other reason might be a practical one. Actual objects take space and their presentation may be time consuming.

More recently, efforts have been made to refine motion capture approaches to provide a standard diagnostic measure for kinematic aspects of apraxia of tool use (Cogollor et al., 2012; Hughes et al., 2013). Movement recordings with sensors allow analysis of spatial trajectories and temporal abnormalities beyond observable aberrations (Clark et al., 1994; Poizner et al., 1995, 1997). The severity of kinematic abnormalities does not necessarily correlate with the frequency of observable conceptual errors in limb apraxia (Hermsdörfer et al., 1996, 2012), supporting the suggestion that conceptual and production components of praxis may be differentially affected (Stamenova et al., 2012) (see below).

Neural correlates

Analyses of the lesions associated with deficits in limb apraxia tests demonstrate left-hemisphere dominance for praxis actions performed with both hands. Lesion symptom mapping of impairments in tool use (Goldenberg and Spatt, 2009) and imitation of meaningless gestures (Mengotti et al., 2013; Buxbaum et al., 2014; Weiss et al., 2014; Goldenberg and Randerath, 2015) indicate that a left frontoparietal-temporal network is involved in these tasks. Deficits in action recognition have been associated with left posterior temporal damage (Kalenine et al., 2010; Tarhan et al., 2015) as well as with lesions in the left inferior frontal gyrus (IFG) (Pazzaglia et al., 2008). Pantomimed tool use deficits have

---

[1] Some authors use the term “tools” to refer to manipulable artifacts (e.g., hammer) and “objects” to refer to their recipients (e.g., nail). We use these terms interchangeably here.

been noted to result from damage to numerous loci in a distributed left-hemisphere network that includes posterior temporal, inferior parietal, and inferior frontal regions (Goldenberg et al., 2007; Price et al., 2010; Buxbaum et al., 2013, 2014; Mengotti et al., 2013; Weiss et al., 2014; Hoeren et al., 2014; Goldenberg and Randerath, 2015). Finally, recent voxel-based lesion symptom mapping of kinematic abnormalities in the execution of tool use movements has revealed associations with the left IFG and insula (Hermsdorfer et al., 2013).

CLASSIC THEORIES OF APRAXIA

At the end of the 19th century, the German linguist Heymann Steinthal (1871, p. 458, part 610) described an aphasic musician who had difficulties grasping tools adequately for their use, including his violin. Steinthal proposed that it is not the movement that is inhibited, but the relation of the mechanism with respect to its function, or the relation of the movement towards the object. Steinthal was the first documented scientist to call the dysfunction apraxia (Steinthal, 1871, p. 458, part 611). He considered apraxia to be an augmentation or amplification of aphasia. The connection to aphasia facilitated the classification of apraxia as a cognitive deficit. Yet, today it is known that at least some characteristics of apraxia can occur independently from aphasia.

Liepmann’s observations

In the beginning of the 20th century, a student of Carl Wernicke, the German neurologist Hugo Liepmann, began to disentangle the heterogeneous disorder. Liepmann received much credit for his work, and by now his descriptive observations have been supported by several modern group studies. Liepmann (1908) demonstrated the dominance of the left hemisphere for purposeful actions of either hand, and showed that aphasia frequently – but not always – co-occurred. He also highlighted the fact that comprehension problems frequently obscured the mechanisms underlying patients’ failure to produce movements requested by the examiner.

In his group study including 47 left-brain-damaged and 42 right-brain-damaged chronic patients, Liepmann (1908) found evidence of apraxia symptoms in 50% of his left-brain-damaged patients. Except for 1 patient, all apraxia patients were aphasic. Imitation of gestures was not as severely impaired as production of the same gestures on verbal command. Nevertheless, patients still demonstrated errors in imitation, which Liepmann ascribed to an inability to direct the limbs according to learned spatial concepts. He observed gesture production to be more error-prone than actual object manipulation. Liepmann reasoned that, in contrast to actual object use, empty-handed gestures have to be fully retrieved from memory and are deprived of visuotactile feedback from external objects. This finding is supported by later group studies (Randerath et al., 2011). However, it should be noted that there are occasional case reports of individuals who perform transitive movements without objects better than the same movements with objects (Brown, 1972; Motomura and Yamadori, 1994; Fukutake, 2003). Further, Liepmann (1908) revealed that, similarly to aphasia, apraxia is clearly associated with left-hemisphere dominance in right- but not left-handers. A group study confirmed an increased variability of lateralization of praxis and language in lefthanded patients with unilateral left- or right-brain damage (Goldenberg, 2013a).

Classifications of limb apraxia

Liepmann (1908) provided an influential theoretical framework for classifying apraxia. He assumed that actions resulted from the participation of the entire brain in creating a concept of goal-directed movements and converting the concept into motor signals. Impairments could occur at different levels of this process. For example, he described cases for which only the production, but not the concept of the movements, was deficient: one of his patients was able to name all the movements he could not produce; another one was not able to produce a waving movement but understood and responded correctly when Liepmann waved for him to imitate. Although Liepmann points out that patients typically show difficulties with more than one aspect, he proposed three basic components of praxis and distinguished different types of apraxia according to the affected component (Liepmann, 1908, 1913, 1920).

Limb kinetic apraxia

Kinetic memory (innervatory patterns) consists of movement formulas for simple or short overlearned movements (e.g., waving). If these kinetic engrams are lost, movement trajectories are executed as if the action is unfamiliar, with reduced smoothness and precision. Imitation as well as spontaneous movements can be disturbed. According to Liepmann (1920, pp. 524–527), limb kinetic apraxia is body part-specific, affecting certain muscle groups (e.g., of the arm, leg, face, or entire head).

Ideomotor or ideokinetic apraxia

According to Liepmann, the kinematic patterns in ideomotor apraxia are preserved, but cannot be willfully retrieved and integrated into the movement plan. Because kinetic and visual or auditory information cannot be combined, imitation and pantomime as well as the use of single objects are impaired in these patients. Typical errors are omissions, substitutions, and movements in wrong directions. Similar to limb-kinetic apraxia, Liepmann believed that ideomotor apraxia affects not all but only certain body parts.

Liepmann designated both limb kinetic and ideomotor/kinetic apraxia as types of motor apraxia.

Ideational apraxia

In a more complex multistep action the temporo-spatial movement formula determines the sequential and spatial procedure as well as which body parts are involved. If this concept is deficient or lost, patients cannot start the action, or demonstrate errors such as omitting aspects or selecting the wrong objects. Simple movements can be imitated. Patients have no problems when presented with defined single steps of the action sequence, except they may demonstrate closely associated alternative movement concepts (e.g., using a hammer by trying to press the nail into the wood). The limbs execute whatever movements were planned. Accordingly, ideational apraxia is not body part-specific. Liepmann emphasizes that it is the ideational concept of the movement that is deficient, and the more steps and objects the action requires, the more drastically the impairment will be exhibited.

Liepmann's classification received broad acknowledgment, and the division into ideational and ideomotor apraxia has been used frequently in the literature. However, due to confusing inconsistencies in the use of terms, and the fact that behaviors consistent with both disorders frequently co-occur in the same patients, the classification has been strongly debated in the last decades (Buxbaum, 2001; Goldenberg, 2013b). As a result, it has been suggested that the distinction is not useful.

A still widely accepted definition of apraxia is the one by Rothi and Heilman (1997), who define apraxia: "as a neurological disorder of learned purposive movement skill that is not explained by deficits of elemental motor or sensory systems" (p. 3). This simple description captures the common aspect of the two major subtypes, defining apraxia as a disorder of motor cognition (i.e., emphasis on learned, purposive skill) while excluding motor dysfunction as a cause. Goldenberg (2013b) similarly considers apraxia as a high-level cognitive intervention on motor control. But he criticizes the long-used exclusion approach in defining limb apraxia and suggests:

> Rather than looking for the limits of apraxia we may look for its core, that is, for manifestations where cognitive interventions on motor control come to the fore most purely. Identification and interpretation of these core deficits will be more fruitful for understanding the nature of apraxia than the attempt to define its limits by compilation of a list of exclusion criteria (p. 220).

In any case, when using the term "apraxia" the types of actions affected should always be described in detail.

Anatomic and cognitive models

The left inferior parietal lobule (IPL) and frontoparietal connections have long been recognized as playing an important role in apraxia. Many early conceptual models described the brain as a serial information-processing system that transforms sensory information into representations that are then used to implement actions. More recently, there has been a trend towards models that allow for more dynamic and integrative processes.

EARLY MODELS—Liepmann (1920) recognized that a large brain network is involved in praxis. He attributed a significant role to the parietal lobe mainly due to the richness of its connecting fibers. Based on his postmortem analysis of lesions in the left hemisphere, he allocated limb kinetic apraxia to more anterior parietal lesions, ideomotor apraxia to more posterior parietal lesions, and assumed parieto-occipital and posterior temporal lesions played a major role in ideational apraxia (Liepmann, 1920, p. 532). In line with Liepmann's observations, modern techniques of functional imaging in healthy adults show a distributed bilateral network activated for tool use, and a dominance of the left hemisphere, including the left parietal lobe (Johnson-Frey, 2004; Lewis, 2006; Frey, 2007, 2008; Vingerhoets, 2008; Brandi et al., 2014).

Geschwind (1975) later provided an anatomic model for the observed left-hemisphere lateralization of the apraxia syndrome with an emphasis on the regions around the sylvian fissure – the sulcus separating the temporal from frontal and parietal lobes. He argued that, when carrying out an action to verbal command, information must pass through these left-hemisphere regions regardless of the hand to be used. He assumed that, after passing through Wernicke's area in the left temporoparietal junction and the left premotor region, action planning for the left hand then crosses the anterior corpus callosum to the right hemisphere's premotor region and precentral motor cortex. In accordance with this model, several case studies have reported unilateral left-sided apraxia in patients with a lesion in the corpus callosum, the major connection between the hemispheres (Liepmann, 1908; Geschwind and Kaplan, 1962; Goldenberg et al., 1985). Unilateral apraxia after callosal "disconnection" is attributed to a lack of interhemispheric transfer.

THE COGNITIVE PRAXIS MODEL—Stimulated by Liepmann's conceptualization of praxis processing and existing language models, Rothi et al. (1997) developed a model of limb apraxia informed by models of language and reading that included several cognitive modules and specified their interactions. Many of the model's components were derived from dissociations of impaired behavior found in patients with limb apraxia. There are three input pathways: auditory verbal, visual object input, and visual gestural input. These are independently processed in lexicons that include different types of memory: a phonologic input lexicon, an object recognition system, and an action input lexicon, containing so-called movement formulas or motor engrams. From these input systems, information is transferred to output systems. For example, visual gestural input is processed by the action output lexicon and subsequently transferred into innervatory patterns for the left and/or right limb's respective motor systems. There is a connection from the input systems to the action semantic system, a repository of acquired action-related knowledge. From there, information can be integrated into the needed output lexicon. There are additional direct pathways, from the input systems to the respective output system, that bypass action semantics. These direct pathways explain imitation of meaningless gestures, as well as the existence of patients who can imitate gestures but not describe or discriminate between them.

Several authors later added components or interconnections to this model. A simplified version of the cognitive model with added components is displayed in Figure 17.1.. For example, Cubelli et al. (2000) included a gestural buffer that holds information for motor planning before the motor response is produced. Furthermore, on the direct pathway between visual analysis and the gestural buffer they inserted a conversion mechanism that supports the transformation of visually analyzed gestures into motor programs. Subsequently, an integrative working memory workspace component, with input from all action systems and output into the gestural buffer and visuomotor conversion mechanism, was added; this workspace explained data of a patient with selective difficulties in pantomime production and working memory (Bartolo et al., 2003). Bartolo et al. (2003) inferred that, for pantomime production, it is necessary to integrate perceptual input and information from action semantics.

Such an integrative working memory component was later incorporated into a model by Randerath (2009), who assumed that this system is fed continuously and in parallel by visual, tactile, and semantic input about objects and gestures. A flexible integrative system would be helpful, for example, when visual feedback is limited. For example, for many tests evaluating the imitation of meaningless gestures, the hand position is close to the head, which limits the ability to use visual feedback. In such cases, it can be observed that healthy participants use alternative strategies (e.g., proprioceptive feedback) to correct their initially erroneous position. The left supramarginal gyrus (SMG: a portion of the IPL) was proposed to be an important neural correlate of such an integrative system (Randerath et al., 2010). Randerath (2009) suggested that the working memory system determines which competing information receives weight, and will be considered for defining the plan, in order to simulate, or actually execute, an intended action. To accommodate this ability, the components and interconnections of the cognitive model need to support continuous input and dynamic interaction between the major systems (as, for example, indicated by two-sided arrow connectors in Fig. 17.1).

A study on different tool use actions and modes revealed two factors explaining most of the variance in the behavioral data. These factors were interpreted as representing a working memory component, and the processing of categorical spatial relationships between hand and body parts, hand and tool, or tools and recipient objects (Randerath et al., 2011). The latter component was originally proposed by Goldenberg (2009), and seen as a major task solved by the parietal lobe. For example, it supports the imitation of meaningless gestures for which body parts are spatially set into relation to each other. Similar to a chunking principle, that is frequently used to facilitate learning, Goldenberg argues that when determining spatial relationships, categorical partitioning (e.g., body part coding into palm, thumb, or mouth) reduces the detail of visual information to be processed as well as the load on working memory. Both components, the analysis of visuospatial relationships as well as the working memory system, may represent commonalities shared by different dysfunctions, potentially explaining overlapping left parietal substrates, for example for the imitation of meaningless gestures (Mengotti et al., 2013; Buxbaum et al., 2014; Hoeren et al., 2014; Weiss et al., 2014; Goldenberg and Randerath, 2015), written language and the token test (Goldenberg and Randerath, 2015), the demonstration of tool use with the tool in hand (Randerath et al., 2010), as well as novel and familiar tool use (Goldenberg and Spatt, 2009). Therefore, Randerath (2009) also fused the spatial relationships component into the cognitive praxis model.

Further, Randerath (2009) proposed bilaterality of a direct route from visual analysis to the working memory system, bypassing the object recognition and semantics system (bilaterality indicated by two parallel arrows in Fig. 17.1). This modification was adopted to explain cases with biparietal lesions demonstrating preserved pantomime but impaired tool use (Motomura and Yamadori, 1994; Fukutake, 2003). Patients with selective actual tool use deficits may have difficulties processing action opportunities (affordances) based on visual information of tool properties delivered bilaterally. Bilateral involvement in affordance perception would also explain why real tool use is less sensitive to unilateral brain damage compared to pantomime of tool use, as the latter likely relies more strongly on semantics and demonstrates strong left lateralization.

THE DUAL-ROUTE MODEL—In the past two decades, traditional cognitive models have largely ceded to more dynamic network hypotheses rooted in neuroanatomic models such as the dual-route model of perception and action. Anatomic studies in monkeys in the 1980s revealed two segregated but interacting visual processing streams in the extrastriate cortex (Ungerleider and Mishkin, 1982; Mishkin etal., 1983): a ventral stream specialized for object knowledge (the "what" system) and a dorsal stream specialized for object localization (the "where" system). The two streams are implemented bilaterally and were similarly found in humans (Goodale and Milner, 1992; Ungerleider and Haxby, 1994).

Goodale and Milner (1992) expanded and modified this neuroanatomic model, assuming a specific underlying organization. On this model, the ventral "what" stream, which projects from occipital to inferior temporal cortex, retrieves representations that have been constructed based on repeated exposures to perceptual information in the environment, and is therefore a "slow" system. Damage therein may lead to visual agnosia for faces or objects. In contrast, the dorsal "how" stream, which projects from occipital cortex to the posterior parietal cortex, processes current perceptual information rapidly and online, for the control of visually guided action. Damage in the parieto-occipital regions of this "fast" dorsal stream system may lead to deficits with goal-directed movements such as reaching to and grasping objects, a disorder known as optic ataxia.

Subsequent research has enabled additional expansion and modification of this framework. For example, neuroanatomic interstream connectivity (Schenk and McIntosh, 2010), as well as patterns of performance in patients (Buxbaum, 2001), indicates that the two streams are richly interactive. Additionally, based both on patient data and monkey neuroanatomic studies, a third stream has been proposed, branching off ventrally from the dorsal stream (Boussaoud et al., 1990; Rizzolatti and Matelli, 2003; Pisella et al., 2006; Rozzi et al., 2006). In the monkey, this ventro-dorsal route starts in the posterior temporal lobule and projects to the IPL (Rizzolatti and Matelli, 2003). According to Rizzolatti and Matelli (2003), the ventro-dorsal route is important for visuospatial perception, and understanding and organization of actions. Damage to this system may bring about unilateral spatial neglect (see Chapter 14).

Consistent with the hypothesis that the IPL is critical for the integration of perceptual inputs and motor outputs (Fogassi and Luppino, 2005; Lewis, 2006; Buxbaum et al., 2007; Frey, 2007), the left ventro-dorsal route has been proposed to play an important role in limb apraxia (Binkofski and Fink, 2005; Buxbaum and Kalénine, 2010; Randerath et al., 2010; Kalénine et al., 2013; Sunderland et al., 2013; Hoeren et al., 2014; Martin et al., 2015). A theoretical approach specifying two dorsal action systems has been proposed by Buxbaum and colleagues (Buxbaum and Kalénine, 2010; Binkofski and Buxbaum, 2013). In this model, the bilateral dorso-dorsal stream represents the "grasp" system, responsible for goal-directed actions based on online processing of structural stimulus information. The left ventro-dorsal stream is characterized as the "use" system, which deals with skilled functional object-related actions, and is concerned with representations of skilled actions associated with familiar objects.

RECENT RESEARCH FINDINGS RELEVANT TO PRAXIS FUNCTIONS OF THE PARIETAL LOBE

Recent data and theoretical models have addressed additional details of the planning and control of skilled action as implemented by the left IPL. In particular, recent evidence has elucidated three important components of skilled actions: (1) representation of tools and the hand as relevant to object manipulation, pantomime, recognition, and imitation; (2) prediction and simulation of movements of the self and others; and (3) selection of actions appropriate to goals and context. The next sections will discuss these IPL functions in turn.

TOOL AND BODY REPRESENTATIONS FOR PRODUCTION, RECOGNITION, AND LEARNING OF ACTIONS

Skillful use of tools, pantomime of tool use actions, knowledge and recognition of object-related actions, and imitation of other’s actions are three related functions that, as described earlier, are frequently disrupted after left parietal damage. These abilities all rely on memories of tool use actions that are implemented by the left IPL and its connections with the left posterior temporal lobe and left IFG. The characteristics and format (e.g., visuospatial or sensorimotor) of these memories, and the most appropriate way to assess their integrity, are issues that are still debated today, more than 100 years after the writings of Steinthal and Liepmann.

Many studies with both neurologically healthy subjects as well as left-hemisphere stroke patients indicate that the left IPL is an important node in the so-called tool use network that represents the manipulation of familiar objects. Space permits review of only a small sample of such studies here. For example, the left IPL is activated during judgments of whether the manipulations associated with two or more objects are the same or different, but not during judgments of tool function (Kellenbach et al., 2003; Boronat et al., 2005). In addition, repetitive transcranial magnetic stimulation to the left SMG disrupts judgments of whether two objects are used with comparable hand postures, and whether a given hand posture is appropriate for using objects (Pelgrims et al., 2011). Other kinds of semantic judgments (tool function and context) were not affected.

Peeters and colleagues (2009) scanned monkeys trained to use simple tools (rake, pliers) and humans while they observed hands grasping and using tools. Whereas activation in the grasping task was the same for humans and monkeys, there was unique activation in the SMG when humans observed other humans using tools. This region is very similar to one described by Valyear and colleagues (2007) as being critical for association of hand actions with functional tool use, and a region found by Buxbaum and colleagues (2006), to be associated with decisions about tool use hand postures.

Chen et al. (2016) used multivoxel pattern analysis to show that the IPL is sensitive to the kinematics of performed pantomimes. They trained a support vector machine pattern classifier to discriminate pairs of tool-related pantomimes (e.g., screwdriver vs. scissors). Whether the classifier could discriminate a new set of items, having action kinematics similar to the old set (e.g., corkscrew vs. pliers), was subsequently tested. Prior to the experiment, a tool localizer task was run to identify tool-preferring regions. Experimental results indicated that several such regions, including the left SMG and left posterior temporal cortex, were sensitive to the similarity of the actions performed in the pantomime task. These data are consistent with results from studies with stroke patients (Kalenine et al., 2010), showing that the SMG is critical for discriminating correctly performed gestures from similar gestures executed with spatial or temporal errors.

Particularly important to rehabilitation and to theoretical models of tool use (Osiurak et al., 2010) is the question of how learning influences tool action representations. Creem-Regehr and colleagues (2007) trained healthy participants on half of a set of novel objects (“tools”) by allowing subjects to observe and then pantomime a novel “use,” and the other half of the set (“shapes”) with grasping and manipulation only, without a specific use. Then, during a scanning session, subjects performed a memory task, imagined grasping, or imagined using all of the objects. In both the memory and imagined use tasks, IPL activation was greater for the “tools” than the “shapes,” indicating that the representation of tools is influenced by experience and extends beyond classically defined affordances.

Barde and colleagues (2007) trained left-hemisphere stroke patients (some with apraxia) to learn the novel gestures for using novel tools by observing pantomimes of the tools being “used.” Subjects were then tested on both a tool gesture-matching task and a pantomime production task. For half the tools, the associated gestures were highly afforded by the tool’s structure, and for the other half they were not. Apraxics performed more poorly overall than non-apraxics, but apraxics whose lesions were more ventral, sparing the dorso-dorsal “grasp” system, performed better on both the production and matching tasks with the highly afforded tools than with the less-afforded tools. Patients whose lesions impinged on the dorso-dorsal stream were not able to benefit from affordances and learned actions poorly with both tool types. This suggests, again, that memories of tool use gestures can be distinguished from affordances derived from object structure, and may be differentially impaired in apraxia (Buxbaum et al., 2003).

An issue of interest in both the apraxia and motor control research communities concerns the significance of the fact that apraxia is frequently observed in both hands of patients with left-hemisphere lesions. This suggests that at least some aspects of apraxia may reflect damage to relatively “abstract” representations in which actions are not coded with respect to specific effectors. Among the possibilities (which are not mutually exclusive) is that these representations are visuospatial (e.g., a shape, or visual image of movement) or occur at a relatively abstract kinematic level (an abstract spatial trajectory) (Wong et al., 2015).

SPATIOTEMPORAL PLANNING AND PREDICTION

The left IPL is also an important locus of processes involved in action planning and prediction. On a number of accounts, predictive sensorimotor control allows the anticipated consequences of movement to serve as a signal to the motor system to correct anticipated errors even before they are produced (Wolpert and Ghahramani, 2000; Kilner et al., 2007). Predictive coding in the parietal lobe has been studied in a number of ways, including anticipation of the grip force needed to lift objects and the postures needed to grasp objects, as well as prediction of the trajectory and timing of others' movements.

Several studies have shown that predictive coding for object lifting based on anticipated weight may be impaired in patients with left parietal lesions. Dawson et al. (2010) showed that patients with left parietal damage and apraxia exhibited abnormal predictive grip force scaling with familiar objects such as a soda can, while performing normally with novel three-dimensional shapes. They interpreted these data in line with the relatively intact ability of apraxic patients with inferior parietal damage – in whom, however, the dorso-dorsal route is spared – to respond to online structural attributes of objects. More recently, Li et al. (2011) showed that damage in the left temporal-parietal-occipital junction (but not apraxia per se) was associated with deficits in anticipatory grip force scaling with objects whose weight violated expectations based on size (i.e., large objects are typically predicted to be heavier than small ones). The relationship between apraxia and anticipatory grip force scaling will be an area of interest for future investigations.

Studies of motor imagery and anticipatory control of movement have also implicated the left IPL. Sirigu and colleagues (1996) showed that left IPL lesions disrupt motor imagery of hand movements without disrupting the movements themselves. Consistent with this, neuroimaging studies have shown that motor imagery and planning actions for their subsequent execution both activate the left IPL (Macuga and Frey, 2012). Buxbaum et al. (2005) demonstrated that lesions involving left IPL disrupt the ability to select from a choice of two the hand posture and wrist rotation subjects would adopt were they to reach out and grasp different-sized three-dimensional shapes at different orientations (i.e., judgment regarding their own prospective movements). Nevertheless, when these subjects were permitted to actually reach out and grasp the shapes, performance was normal, suggesting that they were able to make use of intact visual feedback to correct hand aperture and orientation as the hand approached the objects. This abnormal reliance on feedback in the face of deficits in "feedforward" predictive processes is consistent with data from Jax et al. (2006, 2014), who showed a substantial disruption of apraxics' pantomime ability when they were blindfolded (Haaland et al., 1999; Laimgruber et al., 2005).

The left IPL is also involved in prediction of the movements of others. Accurate prediction of others' movements enhances action understanding and social interaction (Cannon and Woodward, 2012), and is influenced by experience (Abreu et al., 2012; Hudson et al., 2016). A meta-analysis of functional neuroimaging studies showed that motor expertise increases activation in the left SMG, IFG, and precentral gyrus during action observation tasks (Yang, 2015). Recent data from the Buxbaum laboratory (De Wit and Buxbaum, 2017) indicate that deficient predictive processing of others' movements is associated in part with apraxia and IPL damage, even controlling for overall stroke severity. Thus, the involvement of the parietal lobe during prediction of others' movements may reflect adaptive use of the same predictive processes that are used to plan one's own skilled movements.

ACTION SELECTION

An additional function of the IPL relevant to praxis processing is selection of actions appropriate to task goals and context. Long noted in the literature is the tendency of apraxics with posterior parietal damage to produce multiple responses and to have difficulty selecting appropriate movements (DeRenzi and Lucchelli, 1988). More recently, Rushworth and colleagues (2003) noted that the left IPL is involved in the selection and redirection of movements. A related theoretical and computational account by Cisek (2007) incorporates parallel processes of action specification and action selection that account for neurophysiological data and real-time natural interactive behavior. In this model, the dorsal route transforms visual information via the visual cortex and parietal lobe into representations of potential actions. The actions compete against each other in the frontoparietal cortex. This competition is biased by collected information provided by prefrontal regions, the basal ganglia, and the ventral stream, until a single response is selected (Cisek and Kalaska, 2010). Action selection occurs when neural activity reaches a threshold that emerges from the dynamics between the competing populations of cells (Cisek, 2007).

A number of studies with healthy participants indicate that action plans for functional use of objects may interfere with plans appropriate to picking up objects to move them. For example, Jax and Buxbaum (2010) demonstrated that interference is observed when a tool use task precedes a tool-grasping task, and the use and grasp actions are in conflict. An example is a calculator, which is picked up and held with a “clench,” but used with a “poke” posture (Bub et al., 2003, 2008). This indicates that use representations may exert long-lasting competition, even when task-irrelevant. Randerath and colleagues (2013) subsequently showed that such interference is substantially reduced when the grasping task is demanding, and shares computational resources with the use task. They suggested that, under such circumstances, the “new” action plan (i.e., to grasp) may overwrite the previously activated plan (in this case, to use).

Recent data from left-hemisphere stroke patients suggest that response competition is a potent source of action errors in apraxia (Watson and Buxbaum, 2015). Patients were shown photographs of common objects and asked to pantomime their use. Half of the objects were associated with a single, canonical action (e.g., a cup, which is picked up and used with a “clench” hand posture), and the other half of the objects were associated with two or more actions (e.g., a calculator), and were thus termed conflict objects. Avoxel-based lesion symptom mapping analysis showed that, even controlling for other differences between the objects and overall lesion volume, left SMG and IFG damage was associated with disproportionately poor performance with the conflict objects (Fig. 17.2). Moreover, multiple response errors, in which patients made multiple attempts before completing the pantomime trial were more frequent with conflict objects, consistent with a response selection deficit. The authors suggested that the SMG/IFG pathway implements biased competition between tool use actions. The SMG, in particular, was hypothesized to buffer potentially relevant actions in short-term memory until a single action is selected (see also Randerath et al. (2013) for an account emphasizing the role of short-term memory). Subsequently, Rounis and Humphreys (2015) proposed that patients with limb apraxia may be abnormally sensitive to the action opportunities provided by the environment. Such accounts may prove useful in understanding the performance of apraxic patients in real-world tasks (such as meal preparation and grooming), entailing sequential grasping and use of multiple objects, many with different affordances for action.

REHABILITATION STRATEGIES

Limb apraxia may affect various aspects of rehabilitation: impaired imitation of movements aggravates physical therapy, difficulties with gesturing complicates communication, and inadequate object use influences independence in activities of daily living. Despite the obvious relevance, advances in evidence-based rehabilitation strategies for patients with limb apraxia are scanty (for reviews, see Buxbaum et al., 2008; Cantagallo et al., 2012). Gesture training (Cubelli et al., 1991; Daumüller and Goldenberg, 2010) and guided training of activities of daily living (Goldenberg and Hagmann, 1998; Goldenberg et al., 2001) are amongst the few effective approaches tested in small groups. For example, Smania et al. (2006) trained patients to produce object-related gestures to tools, videos, and pictures over many repeated trials. Transfer effects to unlearned activities of daily living may be possible when this type of training is applied with high intensity, variability in the trained items, and the individualization of therapy to patients’ deficits (Smania et al., 2006; Geusgens et al., 2007).

Recently, the effectiveness of neurostimulation techniques has been evaluated. Bolognini et al. (2014) tested the effect of transcranial direct current stimulation (tDCS) for 10 minutes in 6 patients with divergent left-brain damage. tDCS delivered to the left posterior parietal cortex reduced the time required to plan gesture imitation as well as the frequency of errors. Greater parietal damage was associated with smaller improvement. Although the need for follow-up studies is clear, these data appear promising.

Another novelty in limb apraxia rehabilitation is the use of computer and electronics technologies, in order to facilitate single-tool use and multistep actions. For example, in a recent multicenter project, a personal healthcare system prototype for cognitive rehabilitation in a living assistance domain was developed (Bieńkiewicz et al., 2014; Pastorino et al., 2014; Pflügler et al., 2014). In the coming years, demonstrations of the feasibility and effectiveness of technology-based approaches to apraxia rehabilitation will be of great interest.

FUTURE DIRECTIONS AND CONCLUSIONS

Historical accounts of apraxia emphasized characterization of apraxia subtypes (e.g., ideational versus ideomotor) on the basis of error types and patterns of performance with pantomime, single objects, and multiple objects. Unfortunately, such accounts have resulted in ongoing confusion in both clinical and research communities. Owing in part to growing sophistication in lesion analysis approaches, which enable greater statistical certainty about brain–behavior relationships, as well as supporting evidence from functional neuroimaging and neurostimulation studies, classic distinctions are beginning to give way to a more nuanced appreciation of the distributed left-hemisphere network that is critical for skilled actions.

Among the insights from this more recent work is greater understanding of the relationship of the left ventro-dorsal stream (likely projecting from posterior temporal lobe through IPL and on to IFG) to the classically defined (dorso) dorsal and ventral visual pathways. In that context, the left IPL plays specific roles in the representation of tools and the body, planning and prediction, and action selection. While the dorso-dorsal stream is specialized for actions under current visual guidance, the left IPL accesses learned information conveyed from the ventral stream to enable mediation of responses to current object structure by prior learning. While the dorso-dorsal stream is relatively visually feedback-dependent, the left IPL implements a greater degree of predictive processing in which prior knowledge (including the anticipated sensorimotor consequences of planned actions) can be used to reduce the likelihood of error occurrence.

Relevant to its ability to integrate prior learning that may occur in a visuospatial or abstract format, the left IPL (unlike the dorso-dorsal stream) is specialized for skilled movements of both hands. In addition, the left IPL is the locus of a working-memory system that buffers potential responses during action selection. A learning-sensitive system that can prepare multiple actions in parallel and select appropriate actions based on current task relevance and goals is of critical importance to the use of tools in daily life, in which the opportunities for many different actions are considerable.

With these points in mind, we will close with three considerations for future research. The first is that our characterization of the ventro-dorsal stream bears a strong resemblance to theoretical and computational models of the dorsal language pathway in the left hemisphere (Hickok and Poeppel, 2007; Saur et al., 2008). Like the ventro-dorsal action system, the dorsal language pathway projects from posterior temporal regions through the IPL, and into the IFG. And like the ventro-dorsal action system, the dorsal language stream appears to be specialized for prediction and selection of the spatiotemporal aspects of action (in this case, speech), perhaps in a relatively abstract format. Moreover, lesions to the left IPL may give rise to conduction aphasia, which may be characterized in part by deficits in phonological (speech sound) selection and phonological short-term memory (Vallar and Papagno, 2002; see Chapter 18). Although (as noted earlier) the close association of apraxia and aphasia has been noted for over 100 years, consideration of the two disorders in terms of their common mechanisms continues to be an interesting avenue for future research.

A second, related consideration for future research is that, rather than attempting to label subtypes of apraxia based purely on behavior, study of apraxic symptoms should be more closely aligned with evolving and increasingly precise neuroanatomic models of the role(s) of temporal, parietal, and frontal regions in action representation and selection.

For example, evidence that action recognition deficits differentially occur with lesions to the left posterior temporal lobe (such as that shown in Fig. 17.3; Tarhan et al., 2015) should be viewed in the context of our recent understanding of this region's role in representation of visual motion, hands, and tools (Bracci et al., 2012). Lesions to this region may result in loss of the “action concept,” and of patterns of performance that correspond to the classic ideational apraxia (e.g., deficits in gesture recognition; deficient gestures with objects). In contrast, as noted earlier, lesions to the IPL result in deficits in the spatiotemporal aspects of predictive processing, in representing abstract kinematic trajectories, and in buffering actions to enable selection appropriate to current constraints. This account of IPL function predicts that deficits in action imitation and selection will be observed with IPL lesions, consistent with classic ideomotor apraxia. Critically, however, these regions of the tool use network are densely interconnected, such that even relatively discrete lesions to one region may be expected to have upstream and downstream consequences. As a result, a mixture of deficits is the expected pattern in many patients.

Following from this, it should be noted that, while for the purpose of this review we have sketched out a relatively simplistic division of labor, recent advances in functional connectivity analyses are beginning to reveal details of the dense network of white-matter pathways connecting frontal, temporal, and parietal regions of the tool use network (Bi et al., 2015). In addition, study of network connectivity changes with learning is starting to reveal increased connectivity in the frontotemporalparietal tool use network with increased tool use experience (Bellebaum et al., 2013). Future studies of the neuroanatomic substrates of various components of the apraxia syndrome will increasingly benefit from such network connectivity approaches.

Finally, a third consideration for future research is that studies of the rehabilitation of apraxia lag far behind in number, sophistication, and rigor as compared to rehabilitation research in other domains. This may be due in part to the lingering misperception that apraxia is a disorder that appears largely in laboratory contexts, without consequences for real-life actions (DeRenzi et al., 1982), as well as because many apraxics may have reduced awareness of their deficits (Canzano et al., 2016). We suggest that, given the considerable overlap in the neural substrates of apraxia and aphasia, consideration of the “active ingredients” that underlie successful treatments for aphasia may be useful. For example, a successful approach to treatment of naming deficits in aphasia attempts to strengthen the associative links between objects and actions as signified by nouns and verbs (Kiran and Thompson, 2003). A related approach in the apraxia domain might seek to strengthen the associative links between objects, people, locations, and actions. We speculate that such treatments may be particularly useful in patients who are deficient in the more conceptual aspects of tool use action (as indexed, for instance, by impaired gesture recognition). In contrast, approaches emphasizing practice with the more procedural, sensorimotor aspects of skilled action (perhaps with the aid of computer or electronics technologies) may be particularly relevant in patients who are relatively deficient in spatiotemporal processing (as evidenced, for example, by imitation impairments). Testing of these and other related hypotheses with rigorous rehabilitation studies will be of great interest for the future.

REFERENCES

Abreu AM, Macaluso E, Azevedo RT et al. (2012). Action anticipation beyond the action observation network: a functional magnetic resonance imaging study in expert basketball players. Eur J Neurosci 35: 1646–1654. [PubMed: 22541026]

Barde L, Buxbaum L, Moll A (2007). Abnormal reliance on object structure in apraxics' learning of novel actions. J Int Neuropsychol Soc 13: 997–1008. [PubMed: 17942018]

Bartolo A, Cubelli R, Della Sala S et al. (2003). Pantomimes are special gestures which rely on working memory. Brain Cogn 53: 483–494. [PubMed: 14642299]

Bellebaum C, Tettamanti M, Marchetta E et al. (2013). Neural representations of unfamiliar objects are modulated by sensorimotor experience. Cortex 49: 1110–1125. [PubMed: 22608404]

Bi Y, Han Z, Zhong S et al. (2015). The white matter structural network underlying human tool use and tool understanding. J Neurosci 35: 6822–6835. [PubMed: 25926458]

Bieńkiewicz MM, Gulde P, Schlegel A et al. (2014). The use of ecological sounds in facilitation of tool use in apraxia. In: Replace, repair, restore, relieve – bridging clinical and engineering solutions in neurorehabilitation, Cham, Switzerland.

Binkofski F, Buxbaum LJ (2013). Two action systems in the human brain. Brain Lang 127: 222–229. [PubMed: 22889467]

Binkofski F, Fink G (2005). Apraxien. Der Nervenarzt 76: 493–512. [PubMed: 15806418]

Bolognini N, Convento S, Banco E et al. (2014). Improving ideomotor limb apraxia by electrical stimulation of the left posterior parietal cortex. Brain. awu343.

Boronat C, Buxbaum L, Coslett H et al. (2005). Distinctions between manipulation and function knowledge of objects: evidence from functional magnetic resonance imaging. Cogn Brain Res 23: 361–373.

Boussaoud D, Ungerleider LG, Desimone R (1990). Pathways for motion analysis: cortical connections of the medial superior temporal and fundus of the superior temporal visual areas in the macaque. J Comp Neurol 296: 462–495. [PubMed: 2358548]

Bracci S, Cavina-Pratesi C, Ietswaart M et al. (2012). Closely overlapping responses to tools and hands in left lateral occipitotemporal cortex. J Neurophysiol 107: 1443–1456. [PubMed: 22131379]

Brandi M-L, Wohlschläger A, Sorg C et al. (2014). The neural correlates of planning and executing actual tool use. J Neurosci 34: 13183–13194. [PubMed: 25253863]

Brown JW (1972). Aphasia, apraxia, and agnosia: clinical and theoretical aspects, Springfield, Illinois.

Bub D, Masson M, Bukach C (2003). Gesturing and naming: the use of functional knowledge in object identification. Psychol Sci 14: 467–472. [PubMed: 12930478]

Bub DN, Masson ME, Cree GS (2008). Evocation of functional and volumetric gestural knowledge by objects and words. Cognition 106: 27–58. [PubMed: 17239839]

Buxbaum LJ (1998). Ideational apraxia and naturalistic action. Cogn Neuropsychol 15 (6–8): 617–643. [PubMed: 22448839]

Buxbaum LJ (2001). Ideomotor apraxia: a call to action. Neurocase 7: 445–458. [PubMed: 11788737]

Buxbaum LJ, Kalénine S (2010). Action knowledge, visuomotor activation, and embodiment in the two action systems. Ann N Y Acad Sci 1191: 201–218. [PubMed: 20392282]

Buxbaum LJ, Sirigu A, Schwartz MF et al. (2003). Cognitive representations of hand posture in ideomotor apraxia. Neuropsychologia 41: 1091–1113. [PubMed: 12667544]

Buxbaum LJ, Johnson-Frey SH, Bartlett-Williams M (2005). Deficient internal models for planning hand-object interactions in apraxia. Neuropsychologia 43: 917–929. [PubMed: 15716162]

Buxbaum LJ, Kyle KM, Tang K et al. (2006). Neural substrates of knowledge of hand postures for object grasping and functional object use: evidence from fMRI. Brain Res 1117: 175–185. [PubMed: 16962075]

Buxbaum LJ, Kyle K, Grossman M et al. (2007). Left inferior parietal representations for skilled hand-object interactions: evidence from stroke and corticobasal degeneration. Cortex 43: 411–423. [PubMed: 17533764]

Buxbaum LJ, Haaland KY, Hallett M et al. (2008). Treatment of limb apraxia: moving forward to improved action. Am J Phys Med Rehabil 87: 149–161. [PubMed: 18209511]

Buxbaum L, Shapiro A, Coslett H (2013). Separable components of object-related gesture production in the left hemisphere, Society for Neuroscience, San Diego.

Buxbaum LJ, Shapiro AD, Coslett HB (2014). Critical brain regions for tool-related and imitative actions: a componential analysis. Brain. awu111.

Cannon EN, Woodward AL (2012). Infants generate goal-based action predictions. Dev Sci 15: 292–298. [PubMed: 22356184]

Cantagallo A, Maini M, Rumiati RI (2012). The cognitive rehabilitation of limb apraxia in patients with stroke. Neuropsychol Rehabil 22: 473–488. [PubMed: 22324430]

Canzano L, Scandola M, Gobbetto V et al. (2016). The representation of objects in apraxia: from action execution to error awareness. Frontiers in Human Neuroscience 10: 39. [PubMed: 26903843]

Chen Q, Garcea FE, Mahon BZ (2016). The representation of object-directed action and function knowledge in the human brain. Cereb Cortex 26: 1609–1618. [PubMed: 25595179]

Cisek P (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. Philos Trans R Soc Lond B Biol Sci 362: 1585–1599. [PubMed: 17428779]

Cisek P, Kalaska JF (2010). Neural mechanisms for interacting with a world full of action choices. Annu Rev Neurosci 33: 269–298. [PubMed: 20345247]

Clark MA, Merians AS, Kothari A et al. (1994). Spatial planning deficits in limb apraxia. Brain 117: 1093–1106. [PubMed: 7953591]

Cogollor JM, Hughes C, Ferre M et al. (2012). Handmade task tracking applied to cognitive rehabilitation. Sensors 12: 14214–14231. [PubMed: 23202045]

Creem-Regehr SH, Dilda V, Vicchrilli AE et al. (2007). The influence of complex action knowledge on representations of novel graspable objects: evidence from functional magnetic resonance imaging. J Int Neuropsychol Soc 13: 1009–1020. [PubMed: 17942019]

Cubelli R, Trentini P, Montagna CG (1991). Re-education of gestural communication in a case of chronic global aphasia and limb apraxia. Cogn Neuropsychol 5: 369–380.

Cubelli R, Marchetti C, Boscolo G et al. (2000). Cognition in action: testing a model of limb apraxia. Brain Cogn 44: 144–165. [PubMed: 11041987]

Daumüller M, Goldenberg G (2010). Therapy to improve gestural expression in aphasia: a controlled clinical trial. Clin Rehabil 24: 55–65. [PubMed: 20026576]

Dawson AM, Buxbaum LJ, Duff SV (2010). The impact of left hemisphere stroke on force control with familiar and novel objects: neuroanatomic substrates and relationship to apraxia. Brain Res 1317: 124–136. [PubMed: 19945445]

DeRenzi E, Lucchelli F (1988). Ideational apraxia. Brain 111: 1173–1185. [PubMed: 3179688]

De Renzi E, Pieczuro A, Vignolo L (1968). Ideational apraxia: a quantitative study. Neuropsychologia 6: 41–52.

De Renzi E, Faglioni P, Sorgato P (1982). Modality-specific and supramodel mechanisms of apraxia. Brain 105: 301–312. [PubMed: 6177376]

De Wit M, Buxbaum LJ (2017). Critical motor involvement in prediction of human and non-biological motion trajectories. J Int Neuropsychol Soc 23: 171–184. [PubMed: 28205497]

Fogassi L, Luppino G (2005). Motor functions of the parietal lobe. Curr Opin Neurobiol 15: 626–631. [PubMed: 16271458]

Frey SH (2007). What puts the how in where? Tool use and the divided visual streams hypothesis. Cortex 43: 368–375. [PubMed: 17533760]

Frey SH (2008). Tool use, communicative gesture and cerebral asymmetries in the modern human brain. Philos Trans R Soc Lond B Biol Sci 363: 1951–1957. [PubMed: 18292060]

Fukutake T (2003). Apraxia of tool use: an autopsy case of biparietal infarction. Eur Neurol 49: 45–52. [PubMed: 12464718]

Geschwind N (1975). The apraxias: neural mechanisms of disorders of learned movement. Am Sci 63: 188–195. [PubMed: 1115438]

Geschwind N, Kaplan EA (1962). Human cerebral disconnection syndromes. Neurology 12: 675–685. [PubMed: 13898109]

Geusgens C, Van Heugten C, Cooijmans J et al. (2007). Transfer effects of a cognitive strategy training for stroke patients with apraxia. J Clin Exp Neuropsychol 29: 831–841. [PubMed: 18030634]

Goldenberg G (2009). Apraxia and the parietal lobes. Neuropsychologia 47: 1449–1459. [PubMed: 18692079]

Goldenberg G (2013a). Apraxia in left-handers. Brain 136: 2592–2601. [PubMed: 23864275]

Goldenberg G (2013b). Apraxia: the cognitive side of motor control, Oxford University Press, Oxford.

Goldenberg G, Hagmann S (1998). Therapy of activities of daily living in patients with apraxia. Neuropsychol Rehabil 8: 123–141.

Goldenberg G, Randerath J (2015). Shared neural substrates of apraxia and aphasia. Neuropsychologia 75: 40–49. [PubMed: 26004063]

Goldenberg G, Spatt J (2009). The neural basis of tool use. Brain 132: 1645–1655. [PubMed: 19351777]

Goldenberg G, Wimmer A, Holzner F et al. (1985). Apraxia of the left limbs in a case of callosal disconnection: the contribution of medial frontal lobe damage. Cortex 21: 135–148. [PubMed: 3987307]

Goldenberg G, Daumüller M, Hagmann S (2001). Assessment and therapy of complex activities of daily living in apraxia. Neuropsychol Rehabil 11: 147–169.

Goldenberg G, Hermsdorfer J, Glindemann R et al. (2007). Pantomime of tool use depends on integrity of left inferior frontal cortex. Cereb Cortex 17: 2769–2776. [PubMed: 17339607]

Goodale MA, Milner AD (1992). Separate visual pathways for perception and action. Trends Neurosci 15: 20–25. [PubMed: 1374953]

Goodglass H, Kaplan E (1972). The assessment of aphasia and related disorders, Lea and Febiger, Philadelphia.

Haaland KY, Harrington DL, Knight RT (1999). Spatial deficits in ideomotor limb apraxia: a kinematic analysis of aiming movements. Brain 122: 1169–1182. [PubMed: 10356068]

Hermsdorfer J, Mai N, Spatt J et al. (1996). Kinematic analysis of movement imitation in apraxia. Brain 119: 1575–1586. [PubMed: 8931581]

Hermsdörfer J, Li Y, Randerath J et al. (2012). Tool use without a tool: kinematic characteristics of pantomiming as compared to actual use and the effect of brain damage. Exp Brain Res 218: 201–214. [PubMed: 22349499]

Hermsdorfer J, Li Y, Randerath J et al. (2013). Tool use kinematics across different modes of execution. Implications for action representation and apraxia. Cortex 49: 184–199. [PubMed: 22176873]

Hickok G, Poeppel D (2007). The cortical organization of speech processing. Nat Rev Neurosci 8: 393–402. [PubMed: 17431404]

Hoeren M, Kümmerer D, Bormann T et al. (2014). Neural bases of imitation and pantomime in acute stroke patients: distinct streams for praxis. Brain. awu203.

Hudson M, Nicholson T, Simpson WA et al. (2016). One step ahead: the perceived kinematics of others' actions are biased toward expected goals. J Exp Psychol Gen 145: 1–7. [PubMed: 26595838]

Hughes CM, Parekh M, Hermsdörfer J (2013). Segmenting instrumented activities of daily living (IADL) using kinematic and sensor technology for the assessment of limb apraxia. HCI International 2013-Posters' Extended Abstracts, Springer.

Jax SA, Buxbaum LJ (2010). Response interference between functional and structural actions linked to the same familiar object. Cognition 115: 350–355. [PubMed: 20156619]

Jax SA, Buxbaum LJ, Moll AD (2006). Deficits in movement planning and intrinsic coordinate control in ideomotor apraxia. J Cogn Neurosci 18: 2063–2076. [PubMed: 17129191]

Jax SA, Rosa-Leyra DL, Buxbaum LJ (2014). Conceptual-and production-related predictors of pantomimed tool use deficits in apraxia. Neuropsychologia 62: 194–201. [PubMed: 25107676]

Johnson-Frey S (2004). The neural bases of complex tool use in humans. Trends Cogn Sci 8: 71–78. [PubMed: 15588811]

Kalenine S, Buxbaum LJ, Coslett HB (2010). Critical brain regions for action recognition: lesion symptom mapping in left hemisphere stroke. Brain 133: 3269–3280. [PubMed: 20805101]

Kalénine S, Shapiro AD, Buxbaum LJ (2013). Dissociations of action means and outcome processing in left hemisphere stroke. Neuropsychologia 51: 1224–1233. [PubMed: 23566892]

Kellenbach ML, Brett M, Patterson K (2003). Actions speak louder than functions: the importance of manipulability and action in tool representation. J Cogn Neurosci 15: 30–46. [PubMed: 12590841]

Kilner JM, Friston KJ, Frith CD (2007). Predictive coding: an account of the mirror neuron system. Cogn Process 8: 159–166. [PubMed: 17429704]

Kiran S, Thompson CK (2003). The role of semantic complexity in treatment of naming deficits: training semantic categories in fluent aphasia by controlling exemplar typicality. J Speech Lang Hear Res 46: 608–622. [PubMed: 14696989]

Laimgruber K, Goldenberg G, Hermsdorfer J (2005). Manual and hemispheric asymmetries in the execution of actual and pantomimed prehension. Neuropsychologia 43: 682–692. [PubMed: 15721181]

Leiguarda R, Clarens F, Amengual A et al. (2014). Short apraxia screening test. J Clin Exp Neuropsychol 36: 867–874. [PubMed: 25360559]

Lewis J (2006). Cortical networks related to human use of tools. The Neuroscientist 12: 211–231. [PubMed: 16684967]

Li Y, Randerath J, Goldenberg G et al. (2011). Size-weight illusion and anticipatory grip force scaling following unilateral cortical brain lesion. Neuropsychologia 49: 914–923. [PubMed: 21333663]

Liepmann H (1908). Drei Aufsaetze aus dem Apraxiegebiet, Karger, Berlin.

Liepmann P (1913). Motorische Aphasie und Apraxie. Eur Neurol 34: 485–494.

Liepmann H (1920). Apraxie. Ergebnisse der gesamten Medizin 1: 516–543.

Macuga KL, Frey SH (2012). Neural representations involved in observed, imagined, and imitated actions are dissociable and hierarchically organized. Neuroimage 59: 2798–2807. [PubMed: 22005592]

Martin M, Beume L, Kümmerer D et al. (2015). Differential roles of ventral and dorsal streams for conceptual and production-related components of tool use in acute stroke patients. Cereb Cortex. bhv 179.

Mengotti P, Corradi-Dell’Acqua C, Negri GA et al. (2013). Selective imitation impairments differentially interact with language processing. Brain 136: 2602–2618. [PubMed: 23884815]

Mishkin M, Ungerleider LG, Macko KA (1983). Object vision and spatial vision: two cortical pathways. Trends Neurosci 6: 414–417.

Motomura N, Yamadori A (1994). A case of ideational apraxia with impairment of object use and preservation of object pantomime. Cortex 30: 167–170. [PubMed: 8004986]

Osiurak F, Jarry C, Le Gall D (2010). Grasping the affordances, understanding the reasoning: toward a dialectical theory of human tool use. Psychol Rev 117: 517–540. [PubMed: 20438236]

Pastorino M, Fioravanti A, Arredondo MT et al. (2014). Preliminary evaluation of a personal healthcare system prototype for cognitive rehabilitation in a living assistance domain. Sensors 14: 10213–10233. [PubMed: 24922452]

Pazzaglia M, Smania N, Corato E et al. (2008). Neural underpinnings of gesture discrimination in patients with limb apraxia. J Neurosci 28: 3030–3041. [PubMed: 18354006]

Peeters R, Simone L, Nelissen K et al. (2009). The representation of tool use in humans and monkeys: common and uniquely human features. J Neurosci 29: 11523–11539. [PubMed: 19759300]

Pelgrims B, Olivier E, Andres M (2011). Dissociation between manipulation and conceptual knowledge of object use in the supramarginalis gyrus. Hum Brain Mapp 32: 1802–1810. [PubMed: 21140435]

Pflügler J, Schlegel A, Jean-Baptiste E et al. (2014). Using human-computer interface for rehabilitation of activities of daily living (ADL) in stroke patients: lessons from the first prototype. In: Replace, repair, restore, relieve–bridging clinical and engineering solutions in neurorehabilitation, Cham, Switzerland.

Pisella L, Binkofski F, Lasek K et al. (2006). No doubledissociation between optic ataxia and visual agnosia: multiple sub-streams for multiple visuo-manual integrations. Neuropsychologia 44: 2734–2748. [PubMed: 16753188]

Poeck K (1986). The clinical examination for motor apraxia. Neuropsychologia 24: 129–134. [PubMed: 3703231]

Poizner H, Clark MA, Merians AS et al. (1995). Joint coordination deficits in limb apraxia. Brain 118: 227–242. [PubMed: 7895006]

Poizner H, Merians AS, Clark M et al. (1997). Kinematic approaches to the study of apraxic disorders. In: Rothi LJ, Heilman KM (Eds.), Apraxia. The neuropsychology of action. Psychology Press, Hove, UK.

Power E, Code C, Croot K et al. (2010). Florida Apraxia Battery–Extended and Revised Sydney (FABERS): design, description, and a healthy control sample. J Clin Exp Neuropsychol 32: 1–18. [PubMed: 19358011]

Price CJ, Crinion JT, Leff AP et al. (2010). Lesion sites that predict the ability to gesture how an object is used. Arch Ital Biol 148: 243–258. [PubMed: 21175011]

Randerath J (2009). Aspekte des Werkzeuggebrauchs: Vom Greifen bis zur Ausführung - Behaviorale und Neuronale Korrelate der Apraxie, Der Andere Verlag, Tönning.

Randerath J, Goldenberg G, Spijkers W et al. (2010). Different left brain regions are essential for grasping a tool compared with its subsequent use. Neuroimage 53: 171–180. [PubMed: 20600986]

Randerath J, Goldenberg G, Spijkers W et al. (2011). From pantomime to actual use: how affordances can facilitate actual tool-use. Neuropsychologia 49: 2410–2416. [PubMed: 21539849]

Randerath J, Martin KR, Frey SH (2013). Are tool properties always processed automatically? The role of tool use context and task complexity. Cortex 49: 1679–1693. [PubMed: 23026760]

Rizzolatti G, Matelli M (2003). Two different streams form the dorsal visual system: anatomy and functions. Exp Brain Res 153: 146–157. [PubMed: 14610633]

Rothi LJ, Heilman KM (1984). Acquisition and retention of gestures by apraxic patients. Brain Cogn 3: 426–437. [PubMed: 6085679]

Rothi LJG, Heilman KM (1997). Introduction to limb apraxia. In: Apraxia: the neuropsychology of action, Psychology Press, Hove, UK.

Rothi LJG, Ochipa C, Heilman KM (1997). A cognitive neuropsychological model of limb praxis. In: Rothi LJG, Heilman KM (Eds.), Apraxia. The neuropsychology of action. Psychology Press, Hove, UK.

Rounis E, Humphreys G (2015). Limb apraxia and the “affordance competition hypothesis”. Frontiers in Human Neuroscience 9: 429. [PubMed: 26283948]

Rozzi S, Calzavara R, Belmalih A et al. (2006). Cortical connections of the inferior parietal cortical convexity of the macaque monkey. Cereb Cortex 16: 1389–1417. [PubMed: 16306322]

Rushworth MF, Johansen-Berg H, Gobel SM et al. (2003). The left parietal and premotor cortices: motor attention and selection. Neuroimage 20 (Suppl 1): S89–S100. [PubMed: 14597301]

Saur D, Kreher BW, Schnell S et al. (2008). Ventral and dorsal pathways for language. Proc Natl Acad Sci U S A 105: 18035–18040. [PubMed: 19004769]

Schenk T, McIntosh RD (2010). Do we have independent visual streams for perception and action? Cogn Neurosci 1: 52–62. [PubMed: 24168245]

Sirigu A, Duhamel J-R, Cohen L et al. (1996). The mental representation of hand movements after parietal cortex damage. Science 273: 1564–1568. [PubMed: 8703221]

Smania N, Aglioti SM, Girardi F et al. (2006). Rehabilitation of limb apraxia improves daily life activities in patients with stroke. Neurology 67: 2050–2052. [PubMed: 17159119]

Stamenova V, Black SE, Roy EA (2012). An update on the Conceptual-Production Systems model of apraxia: evidence from stroke. Brain Cogn 80: 53–63. [PubMed: 22634032]

Steinthal H (1871). Abriss der Sprachwissenschaft, Dümmler, Berlin.

Sunderland A, Wilkins L, Dineen R et al. (2013). Tool-use and the left hemisphere: what is lost in ideomotor apraxia? Brain Cogn 81: 183–192. [PubMed: 23262173]

Tarhan LY, Watson CE, Buxbaum LJ (2015). Shared and distinct neuroanatomic regions critical for tool-related action production and recognition: evidence from 131 left-hemisphere stroke patients. J Cogn Neurosci: 1–21.

Tessari A, Toraldo A, Lunardelli A et al. (2015). STIMA: a short screening test for ideo-motor apraxia, selective for action meaning and bodily district. Neurol Sci: 1–8. [PubMed: 26017501]

Ungerleider LG, Haxby JV (1994). What’ and ‘where’ in the human brain. Current Opinions in Neurobiology 4: 157–165.

Ungerleider LG, Mishkin M (1982). Two cortical visual systems. In: Ingle DI, Mansfield RJW (Eds.), Analysis of visual behavior. MIT Press, Cambridge, MA.

Vallar G, Papagno C (2002). Neuropsychological impairments of verbal short-term memory. In: Baddeley A, Wilson B, Kopelman M (Eds.), Handbook of memory disorders. Wiley, Chichester, England, pp. 249–270.

Valyear KF, Cavina-Pratesi C, Stiglick AJ et al. (2007). Does tool-related fMRI activity within the intraparietal sulcus reflect the plan to grasp? Neuroimage 36 (Suppl 2): T94–T108. [PubMed: 17499175]

Vanbellingen T, Kersten B, Van de Winckel A et al. (2010a). A new bedside test of gestures in stroke: the apraxia screen of TULIA (AST). J Neurol Neurosurg Psychiatry 2010: 213371.

Vanbellingen T, Kersten B, Van Hemelrijk B et al. (2010b). Comprehensive assessment of gesture production: a new test of upper limb apraxia (TULIA). Eur J Neurol 17: 59–66. [PubMed: 19614961]

Vingerhoets G (2008). Knowing about tools: neural correlates of tool familiarity and experience. Neuroimage 40: 1380–1391. [PubMed: 18280753]

Watson CE, Buxbaum LJ (2015). A distributed network critical for selecting among tool-directed actions. Cortex 65C: 65–82.

Weiss PH, Ubben SD, Kaesberg S et al. (2014). Where language meets meaningful action: a combined behavior and lesion analysis of aphasia and apraxia. Brain Structure and Function: 1–14.

Weiss-Blankenhorn P, Eschenbeck P (2014). Kölner Apraxie-Screening–Praktisch bei Apraxie. Ergopraxis 7: 38–39.

Wolpert DM, Ghahramani Z (2000). Computational principles of movement neuroscience. Nature Neuroscience Supplement 3: 1212–1217.

Wong AL, Haith AM, Krakauer JW (2015). Motor planning. Neuroscientist 21 (4): 385–398. [PubMed: 24981338]

Yang J (2015). The influence of motor expertise on the brain activity of motor task performance: a meta-analysis of functional magnetic resonance imaging studies. Cognitive, Affective and Behavioral Neuroscience 15: 381–394.

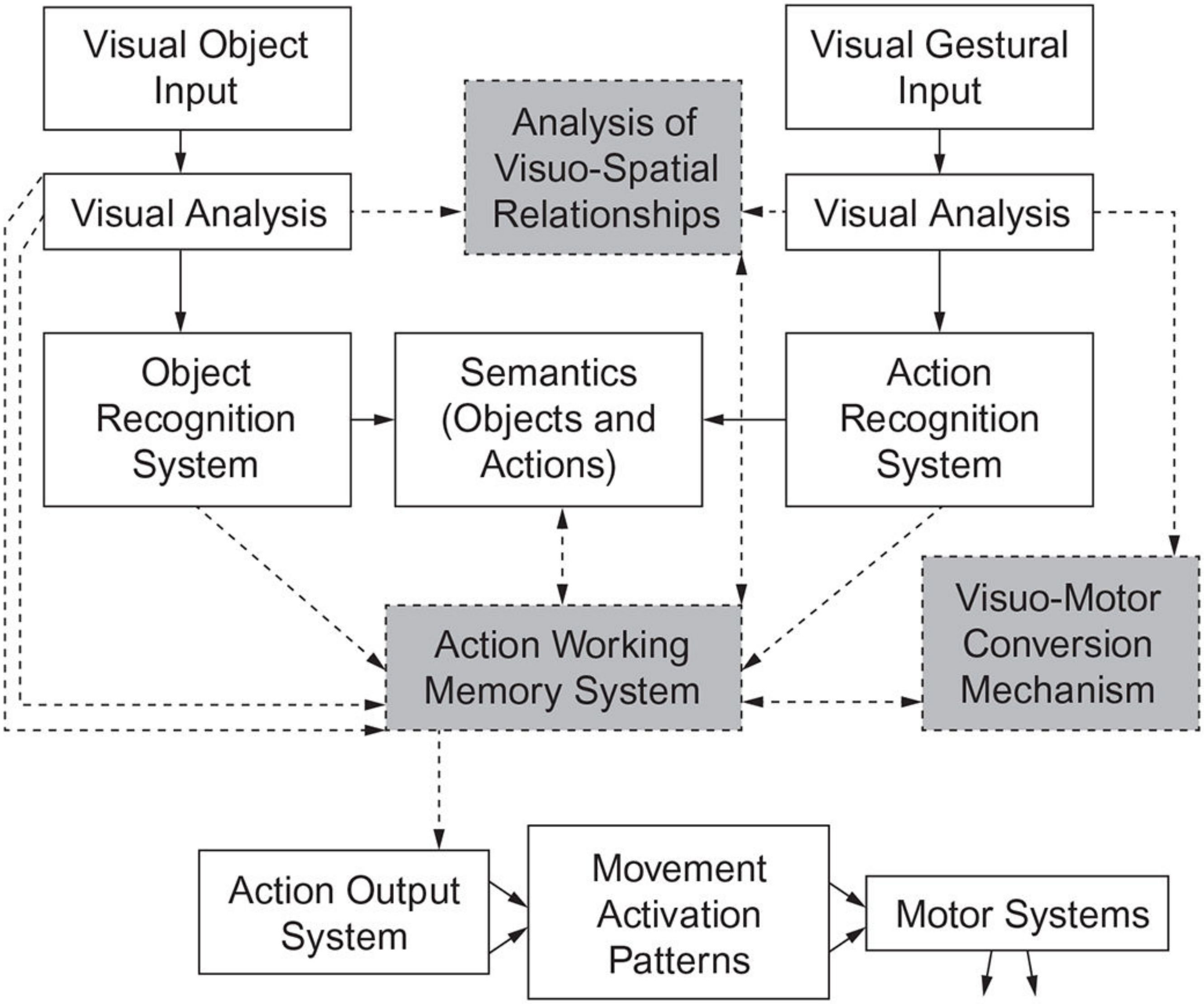

Fig. 17.1.

A simplified cognitive praxis model, adapted from Rothi et al. (1997), including extensions suggested by Cubelli et al. (2000), Bartolo et al. (2003), and Randerath (2009). Extensions are indicated by gray boxes and dashed lines and explained in the text.

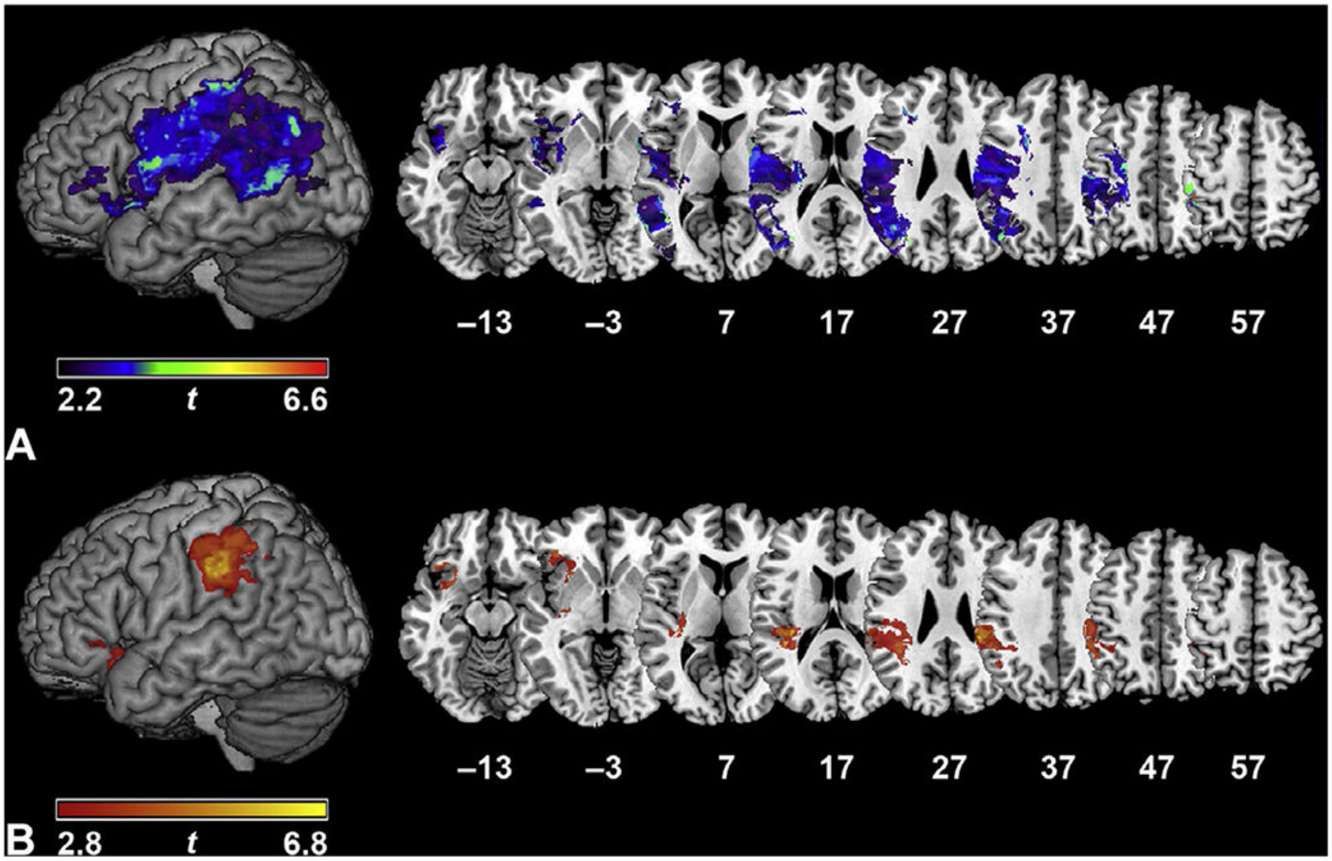

Fig. 17.2.

(**A**) Voxel-based lesion symptom-mapping analysis for overall tool use pantomime accuracy; false discovery rate, $q = 0.05$. (**B**) Voxels in the supramarginal gyrus and inferior frontral gyrus associated with deficient hand action score for "conflict" tools that are associated with more than one action, controlling for scores with "nonconflict" tools associated with one primary action, $q = 0.05$. (Reproduced from Watson CE, Buxbaum LJ (2015) A distributed network critical for selecting among tool-directed actions. Cortex 65C: 65–82, with permission.)

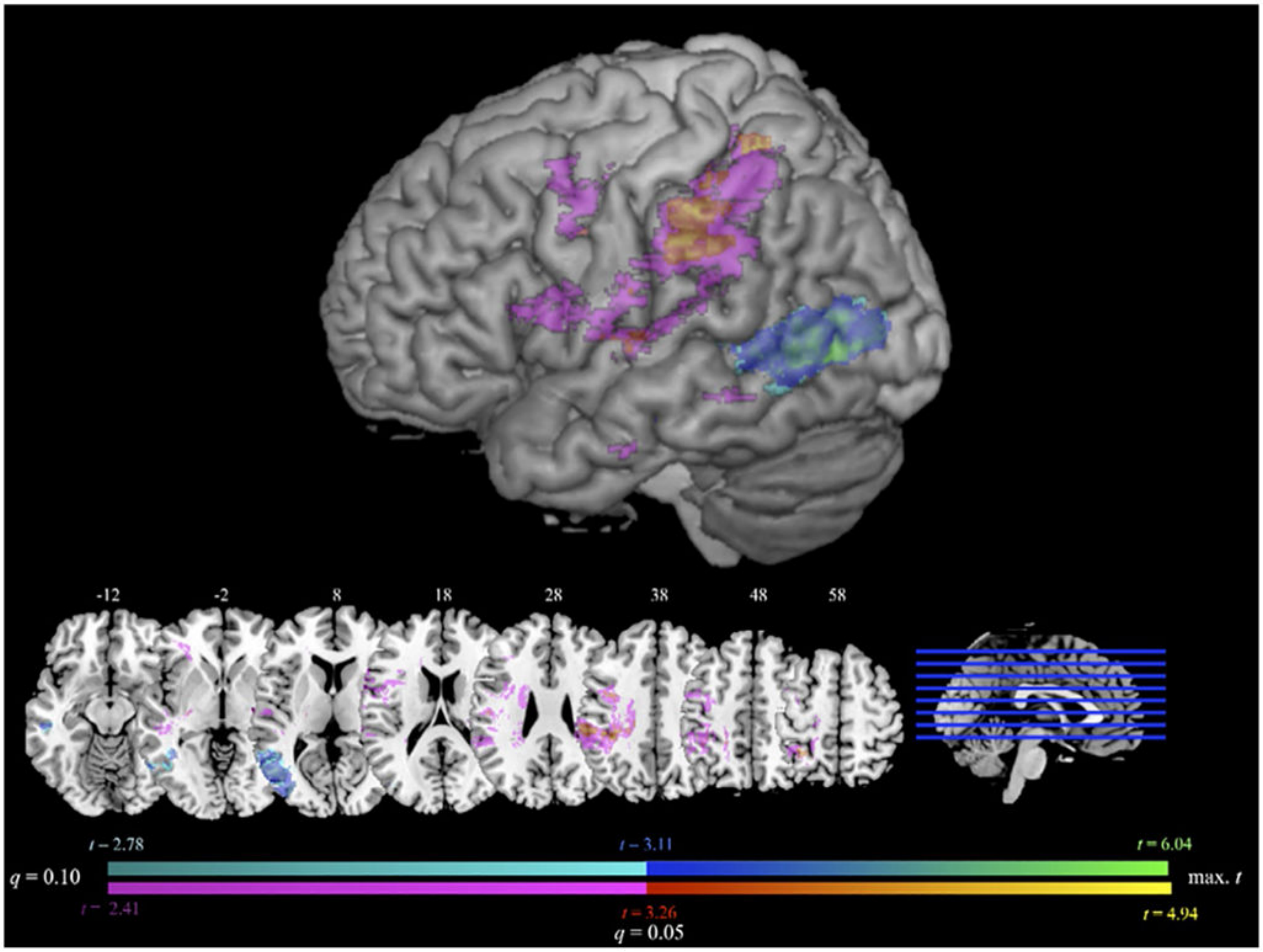

Fig. 17.3.

Voxel-based lesion symptom-mapping analysis of data from 131 patients showing voxels predicting tool action production controlling for recognition (pink/yellow) and vice versa (blue/green). False discovery rate, $q = 0.05$. (Reproduced from Tarhan LY, Watson CE, Buxbaum LJ (2015) Shared and distinct neuroanatomic regions critical for tool-related action production and recognition: evidence from 131 left-hemisphere stroke patients. J Cogn Neurosci 1–21,with permission from MIT Press.)