Treatment of Limb Apraxia
Moving Forward to Improved Action

ABSTRACT

Limb apraxia is a common disorder of skilled, purposive movement that is frequently associated with stroke and degenerative diseases such as Alzheimer disease. Despite evidence that several types of limb apraxia significantly impact functional abilities, surprisingly few studies have focused on development of treatment paradigms. Additionally, although the most disabling types of apraxia reflect damage to gesture and/or object memory systems, existing treatments have not fully taken advantage of principles of experience known to affect learning and neural plasticity. We review the current state of the art in the rehabilitation of limb apraxia, indicate possible points of contact with the learning literature, and generate suggestions for how translational principles might be applied to the development of future research on treatment of this disabling disorder.

Key Words: Apraxia, Ideomotor Apraxia, Treatment, Rehabilitation

 DEFINITIONS OF APRAXIA

Apraxia is a common disorder of skilled, purposive movements. Praxis is mediated by a complex system that stores components of skilled movements, thus providing them a processing advantage (i.e., in terms of accuracy and response time) compared with less-practiced movements. Although several types of apraxia have clear impact on functional abilities and are common consequences of stroke, Alzheimer disease, and corticobasal degeneration, fundamental knowledge in a number of areas necessary to guide informed treatment is surprisingly lacking. There remains confusion about the definitions, distinctiveness, and mechanisms of various types of apraxia and, indeed, whether any have critical functional significance. In addition, although the most disabling types of apraxia reflect damage to systems involved in movement and gesture representation (i.e., memory), the nascent apraxia-treatment literature has not taken advantage of principles of experience known to affect skill learning. The aim of this article is to review the current state of the art in the rehabilitation of limb apraxia and, on the basis of the learning and plasticity literature, generate suggestions for how translational principles might be applied to guide future treatment research.
to describe a decrease or disorder in the ability to perform purposeful, skilled movements. The greatest advance in the description and understanding of these disorders is contained in a series of papers written between 1900 and 1920 by Hugo Liepmann.2–4 Liepmann described three forms of apraxia and, by virtue of his careful evaluations and discussions, brought about a paradigmatic shift in our understanding of motor control. These three types were limb kinetic apraxia (also called melokinetic apraxia or innervatory apraxia), ideomotor apraxia, and ideational apraxia. To this triad, Hanna-Pladdy and Rothi5 and Ochipa et al.6–7 added another type, termed conceptual apraxia, and DeRenzi et al.8 as well as Heilman et al.9 described a fifth type, now called dissociation apraxia.

In this manuscript, we will focus on ideomotor apraxia (hereafter, IMA), for two reasons. First, as will be discussed, it is extremely common in stroke and degenerative disease (Alzheimer disease and corticobasal degeneration). Second, it is increasingly recognized that IMA has important functional consequences, and the disorder is, thus, in need of continued critical investigation, particularly in the area of treatment.

IMA is usually diagnosed on the basis of spatiotemporal errors in the production of transitive (object-related) gesture pantomime to sight of objects, to command, and on imitation of others.10–14 Kinematic analyses have revealed that IMA patients pantomime skilled tool-use movements with abnormal joint angles and limb trajectories, and with uncoupling of the spatial and temporal aspects of movement.15 Spatiotemporal errors persist to a lesser degree with actual tool use.15,16 The deficit is not restricted to meaningful movements, and it has also been observed in meaningless postures17–19 and sequences.20,21 IMA is also associated with cognitive deficits in declarative knowledge of the action appropriate to objects,22 impairments in mechanical problem solving,23 deficits in motor planning,24–26 and difficulty learning new gestures.27,28 Testing for IMA frequently includes pantomimic to command of transitive (familiar actions with objects, such as brushing teeth) and intransitive (symbolic movements without objects, such as the sign for “crazy”) movements, imitation of the examiner performing transitive, intransitive, and novel meaningless movements, and gesture in response to seeing and holding actual tools, as well as the objects on which tools act.

Several investigators have distinguished between IMA with impaired gesture recognition (representational IMA) and IMA with intact recognition (dynamic IMA).29,30 In representational IMA, an inability to discriminate correctly from incorrectly performed meaningful object-related hand movements correlates strongly with an ability to produce the same movements, suggesting that the same representations are likely to underlie both.31 Additionally, representational (but not dynamic) IMA patients are significantly more impaired when producing object-related than symbolic, non-object-related movements.32 This, in turn, suggests that the damaged system underlying representational IMA is specialized for movements related to skilled object use.

**THE FUNCTIONAL IMPLICATIONS OF LIMB APRAXIA: DOES LIMB APRAXIA MATTER IN THE REAL WORLD?**

Historically, most clinicians and researchers believed that limb apraxia had little or no real-world implications.4,10,33–35 This is emphasized by DeRenzi,35a who wrote that “apraxia rarely appears in everyday situations and spontaneous motor behavior, predominantly emerging when gestures are produced out of context as a purposeful response to an artificial request.” Although not specified, it seems that this view was particular to IMA and stemmed from the notion that apraxia was present when pantomimes to command and imitation were tested but improved when the use of actual objects were examined.

It is now widely believed that IMA impairs real-world functioning, but there are still remarkably few studies demonstrating such a relationship. In addition, most studies to date have been fraught with problems. First, these studies usually have not ruled out the influence of all other factors, such as hemiparesis. They commonly have compared the performance of apraxic and nonapraxic patients with left-hemisphere damage,36–41 but, relative to nonapraxics, apraxics are often more impaired in other domains, such as language, sensory, and motor skills. Therefore, it is difficult to know whether limb apraxia is the best predictor of functional skills. Second, apraxics typically have larger lesions than do patients without apraxia, and those lesions more frequently damage the left-parietal and frontal regions,42 which are also important for many other cognitive functions that could, again, confound the findings. Regression approaches have been used to evaluate the unique impact of various factors, including limb apraxia, on activities of daily living (ADLs),43–45 in some cases after controlling statistically for factors such as lesion size, primary motor deficits, and/or other cognitive deficits. However, these studies usually have suffered from statistical problems related to a small number of subjects relative to the number of predictors examined.

Another problem in efforts to understand the influence of apraxia on disability concerns the use of a wide variety of functional measures,
TREATMENT OF LIMB APRAXIA

A recent review of the literature on the treatment of limb apraxia yielded reports of ten treatment approaches, many of which were single-case studies. Methods reported were varied and can be summarized as follows.

Multiple Cues

The multiple-cues treatment method was developed in 1991 by Maher et al. for a 55-yr-old male with chronic ideomotor apraxia and intact gesture recognition. It focused on treatment of gestures, using presentation of multiple cues, including tools, objects, visual models, and feedback. Errors were corrected using imitation and physical manipulation. As performance improved, cues were systematically withdrawn. The individual participated in daily, 1-hr sessions for 2 wks. The multiple-cues method resulted in positive effects, with treated gestures showing some lasting improvement. Generalization to untreated gestures was not assessed.

Error Reduction

In an attempt to define the active components of the multiple-cues method, Ochipa and colleagues conducted a treatment study aimed at treating specific error types. Two males (44 and 66 yrs old) with chronic Broca aphasia and ideomotor apraxia, but preserved gestural recognition, participated in the treatment. Treatment duration and intensity varied, with the 44-yr-old receiving treatment four times per week (n = 44 sessions) and the 66-yr-old receiving treatment two times a day, twice a week (n = 24 sessions). The goals of treatment consisted of reduction of external configuration, movement, and internal configuration errors, depending on the error types exhibited by the individual. Reduction of external configuration errors involved training the individual to correctly orient his hand to objects, whereas reduction of internal configuration errors involved positioning of the hand and fingers to accommodate a tool. Movement errors were reduced through verbal descriptions to guide joint movement while gesturing. Only one error type was addressed at a time, and feedback was only provided about the error type being trained. Error-reduction treatment resulted in a significant and lasting improvement on treated gestures for both individuals. However, no generalization to untreated error types or gestures was noted. Improvements were noted to continue at the 2-wk posttreatment follow-up, but later follow-ups were not performed.

Six-Stage Task Hierarchy

The task hierarchy method was developed by Code and Gaunt, who studied an individual with severe chronic aphasia, ideomotor apraxia, and ideational apraxia. This six-stage task hierarchical treatment for limb apraxia was a modification of an eight-step continuum used to treat apraxia of speech. The Code–Gaunt method requires the patient to produce target words and signs in various combinations and in concert with the therapist in response to a therapist model or picture elicitation. The patient participated in 45-min sessions once weekly for 8 mos. The six-stage task hierarchy method resulted in acquisition of trained signs and
a nonsignificant trend toward improvement in untrained signs during treatment. Maintenance of effects was not formally tested, but the authors provide anecdotal reports of the patient’s continued use of signs in group treatment sessions. Treatment did not impact limb apraxia.

**Conductive Education**

The conductive education method was developed by Pilgrim and Humphreys for a patient with head injury and chronic unimanual apraxia of the nondominant limb. Treatment focused on a task analysis of the movements and articulation of goal-directed tasks. The treatment began with physical manipulation plus verbalization of task elements (e.g., “reach the beaker, clasp the beaker, carry to my lips, drink, stop”), and those cues were systematically withdrawn as performance improved. There were daily 15-min sessions for 3 wks. The conductive education method improved this patient’s performance on treated items compared with untreated items. There was no generalization to untreated objects. Maintenance of effects was not assessed.

**Strategy Training**

The strategy training method was developed as a compensatory technique for individuals with ADL impairment secondary to apraxia. This method was first described in the literature in a study of 33 individuals with apraxia secondary to left-hemisphere stroke. The patients were trained on three ADLs, and the specific method of treatment was chosen according to each individual’s performance in baseline testing of those tasks. A similar strategy training method using five ADLs was studied in another group of 56 individuals with left-hemisphere stroke and subsequent apraxia. Both strategy training approaches focused on the use of internal compensatory strategies (i.e., self-verbalization) and external compensatory strategies (i.e., use of pictures) to maximize independence. The duration and intensity of treatments varied among individuals in both studies. Strategy training resulted in positive outcomes across all domains measured (effect sizes were 0.37 for the ADL tasks and 0.47 for the Barthel ADL index; both were significantly greater than for patients receiving usual occupational therapy treatment), but the improvements were not lasting. In the final study in this series, there was an additional finding of interest—namely, maintenance of gains in trained tasks at 5-mo follow-up.

**Transitive/Intransitive Gesture Training**

The transitive/intransitive gesture training method was investigated by Smania and colleagues in 22 individuals at least 2 mos after onset of a left-hemisphere stroke with subsequent ideomotor limb apraxia. Treatment focused on the training of transitive and intransitive gestures. Transitive gesture training consisted of three phases in which the individual was (1) shown use of common tools, (2) shown a static picture of a portion of the transitive gesture and asked to produce the pantomime, and (3) shown a picture of a common tool and asked to produce the associated gesture. The intransitive gesture training also consisted of three phases in which the individual was (1) shown two pictures, one illustrating a context and the other showing a related symbolic gesture, and asked to reproduce the gesture; (2) shown the context picture alone and asked to reproduce the gesture; and (3) shown a picture of a different but related contextual situation and asked to reproduce the gesture. Fifty-minute treatment sessions were administered three times per week for approximately 10 wks, with the number of total treatment sessions ranging from 30 to 35. A control group was administered aphasia treatment only for a similar intensity and duration. Results indicated a difference between the two groups after treatment, with the gesture training method resulting in improved performance on an IMA test ($U = 69.00, P = 0.016$), a gesture comprehension test ($U = 64.00, P = 0.018$), and an ADL questionnaire ($U = 53.50, P < 0.01$). Importantly, patients and caregivers reported more independence in ADLs after treatment. Nine patients showed maintenance of gains at 2 mos after treatment.

**“Rehabilitative Treatment”**

Smania and colleagues reported a positive outcome with a so-called rehabilitative treatment. It was noted that the treatment was “devised to treat a wide range of gestures and to reduce several types of praxic errors” and that it “used different contextual cues to teach patients how to produce the same gesture under different contextual situations.” Thus, although details were not provided, the treatment seems substantially similar to the one previously reported by this group. Forty-one postacute left-hemisphere stroke patients with limb apraxia (either ideational or IMA—not defined) were assigned randomly to treatment or no-treatment groups. The no-treatment group received aphasia therapy only for a similar intensity and duration. Results indicated a difference between the two groups after treatment, with the errorless completion/exploration training method resulting in improved performance ($P < 0.016$), a gesture comprehension test ($P < 0.018$), and an ADL questionnaire ($P < 0.01$). Importantly, patients and caregivers reported more independence in ADLs after treatment. The no-treatment group received aphasia therapy. Patients attended 30 × 50-min sessions during the course of 10 wks. Although the groups were equivalent in ADL performance, apraxia scores, and ADL questionnaire scores before treatment, they differed significantly on these measures after treatment, both immediately and after a 2-wk delay.

**Errorless Completion + Exploration Training**

The errorless completion/exploration training method was developed by Goldenberg and Hag-
menn\textsuperscript{51} for 15 individuals with IMA (impairment on gesture imitation and gesture to sight of objects) who were, on average, 6.1 wks since onset of a left-hemisphere stroke with subsequent aphasia and severe limb apraxia. The errorless completion method used physical manipulation during ADLs, simultaneous demonstration of ADL by the examiner and imitation by the patient, and copy by the patient after demonstration during performance of three ADLs. The exploration training method directed attention to functional significance of details and critical features of action but did not incorporate direct practice of actions with actual objects. These two methods were combined and treatment was applied to one ADL at a time daily for 20–40 mins for 2–5 wks. Combined errorless completion/exploration training resulted in positive effects that were lasting for individuals who remained active in ADLs at home. A subsequent study was conducted by Goldenberg et al.\textsuperscript{37} comparing these two methods in six individuals with left-hemisphere stroke and subsequent chronic aphasia and limb apraxia. Each treatment type was applied on a different pair of ADLs. The exploration training method had no effect. The errorless completion method yielded a positive and lasting effect. When different objects were used to test ADL, however, the rate of errors increased, and were comparable with untrained gestures. Therefore, there was no evidence of generalization.

**SUMMARY OF TREATMENT LITERATURE**

Table 1 provides a summary of the ten apraxia treatment approaches discussed in the literature to date. Several trends are worth noting. First, apraxia type is frequently poorly characterized. For example, although gesture recognition is clearly an important index of the integrity of gesture representations (which, in turn, may have important implications for rehabilitation strategies), recognition testing is usually not performed. Second, whereas some studies provide data on treatment effects and generalization to untreated items, they are more sparse with regard to treatment effects on degree or nature of limb apraxia, maintenance of treatment effect, and impact of treatment on ADLs. Third, the duration and intensity of treatment differs within and across studies, making it difficult to determine the active components of the treatment. Fourth, the length of time between termination of treatment and follow-up differs across studies, which renders it difficult to compare the lasting effects of treatment on limb apraxia or ADLs. Finally, methods such as the nature of the feedback or correction are commonly underspecified in these reports if described at all, making replication in additional subjects nearly impossible. Despite these issues, the data consistently suggest that intervention yields a treatment effect. Furthermore, in the cases where it is reported, there is indication of maintenance of treatment effects, and impact on nature/degree of limb apraxia as well as on ADL facility. Thus, it seems that the evidence based on these ten Phase I studies suggests that limb apraxia is amenable to treatment. However, according to Robey and Schultz,\textsuperscript{71} the purpose of Phase I research is to develop hypotheses, protocols, and methods; establish safety and activity; determine the best outcome measures; identify responders vs. nonresponders; determine optimal intensity and duration; and determine why the treatment is producing an effect.\textsuperscript{71} Little of this information is found in these ten reports, and, thus, we must continue to promote systematic inquiry until the objectives of Phase I research are satisfied for limb apraxia.

Evidence suggests that nine of the ten treatments reported in the literature yielded a treatment effect. However, only four of these nine treatments resulted in generalization. Because the ultimate goal of rehabilitation is the use of acquired skill in the individual’s natural environment, it is important to consider why certain treatments resulted in generalization, whereas others did not.

Nadeau et al.\textsuperscript{72} recently have identified seven treatment attributes that may contribute to generalization in language rehabilitation: (1) intrinsic: application of knowledge acquired in therapy; (2) cross function: development of knowledge that can be applied to multiple tasks; (3) extrinsic: acquisition of a technique that can be applied outside of treatment to rebuild function (requires motivation); (4) mechanistic: training of key brain resources (i.e., working memory capacity, distributed concept representations, intentional bias); (5) substrate mediated: development of a critical mass of skill needed to further the therapeutic process—necessary for intrinsic/extrinsic mechanisms to operate; (6) contextual: learning environment resembles retrieval environment; and (7) socially mediated: restoration of social context and change in perception regarding roles to promote activity in the environment.

Unfortunately, in the realm of apraxia rehabilitation, there is no clear relationship between these putatively critical mechanisms and treatment generalization. All four treatments that generalized included cross function and extrinsic mechanisms, but some treatments that did not generalize included these mechanisms as well. Similarly, some treatments that were mechanistic generalized, whereas others did not. Of the three treatments that incorporated home practice (contextual mechanism), none resulted in generalization. In addition, on the basis of the available information,
<table>
<thead>
<tr>
<th>Apraxia Type(s)</th>
<th>Trained Items</th>
<th>Duration</th>
<th>Intensity</th>
<th>Treatment Effect</th>
<th>Generalization</th>
<th>Maintenance</th>
<th>Apraxia Impact</th>
<th>ADL Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple cues ($n = 1$)</td>
<td>IMA</td>
<td>Gestures</td>
<td>2 wks</td>
<td>1 hr daily</td>
<td>Y</td>
<td>Y</td>
<td>Y—treated items only (2 wks)</td>
<td>NA</td>
</tr>
<tr>
<td>Error type reduction ($n = 2$)</td>
<td>IMA</td>
<td>Gestures</td>
<td>Varied; 6–11 wks</td>
<td>Varied; once daily 4 days/wk or twice daily 2 days/wk</td>
<td>Y</td>
<td>N</td>
<td>Y—treated error types only (2 wks)</td>
<td>N</td>
</tr>
<tr>
<td>Six-stage task hierarchy ($n = 1$)</td>
<td>IMA + IA</td>
<td>Gestures</td>
<td>8 mos</td>
<td>45 mins; once weekly</td>
<td>Y</td>
<td>N</td>
<td>NA</td>
<td>N</td>
</tr>
<tr>
<td>Conductive education ($n = 1$)</td>
<td>IMA</td>
<td>Gestures</td>
<td>3 wks</td>
<td>Daily</td>
<td>Y</td>
<td>N</td>
<td>NA</td>
<td>N</td>
</tr>
<tr>
<td>Strategy training ($n = 89$)</td>
<td>IA?*</td>
<td>ADL</td>
<td>Varied; 8–12 wks</td>
<td>Varied; 25 sessions, 15 hrs total</td>
<td>Y</td>
<td>Y</td>
<td>N (5 mos)</td>
<td>Y</td>
</tr>
<tr>
<td>Transitive/intransitive gesture training ($n = 13$)</td>
<td>IMA</td>
<td>Gestures</td>
<td>10–11 wks</td>
<td>35 sessions, 50 mins each</td>
<td>Y</td>
<td>Y</td>
<td>NA</td>
<td>Y</td>
</tr>
<tr>
<td>Rehabilitative treatment ($n = 20$)</td>
<td>IA or IMA</td>
<td>Gestures</td>
<td>10 wks</td>
<td>30 sessions, 50 mins each</td>
<td>Y</td>
<td>Y</td>
<td>Y (2 wks)</td>
<td>Y</td>
</tr>
<tr>
<td>Errorless completion + exploration training ($n = 15$)</td>
<td>NA</td>
<td>ADL</td>
<td>2–5 wks</td>
<td>5 days/wk plus 20–40 mins of practice daily</td>
<td>Y</td>
<td>N</td>
<td>Y (6–30 mos)</td>
<td>NA</td>
</tr>
<tr>
<td>Errorless completion ($n = 6$)</td>
<td>IMA</td>
<td>ADL</td>
<td>2 wks</td>
<td>6 sessions, 1 hr each</td>
<td>Y</td>
<td>N</td>
<td>Y (3 mos)</td>
<td>NA</td>
</tr>
<tr>
<td>Exploration training ($n = 6$)</td>
<td>IMA</td>
<td>ADL</td>
<td>2 wks</td>
<td>6 sessions, 1 hr each</td>
<td>Y</td>
<td>N</td>
<td>N (3 mos)</td>
<td>NA</td>
</tr>
</tbody>
</table>

IMA, ideomotor apraxia; IA, ideational apraxia; Y, yes; N, no; NA, not assessed/no information provided.

* Inability to carry out purposeful activities.
arguably akin to what we commonly term praxis. A number of motor learning studies, however, have used complex, learned actions that are toward applying this literature to the study of IMA.

Some of the actions typically assessed in motor learning studies differ in complexity and/or meaningfulness from the skilled actions that comprise praxis. A number of motor learning studies, however, have used complex, learned actions that are arguably akin to what we commonly term praxis movements. Other motor learning studies have examined complex spatiomotor transformations that may have relevance to spatial coding of complex action. Thus, it is important to carefully examine the motor learning literature for points of possible convergence with the study of learning in apraxia.

Neuroanatomical Considerations

The primary motor cortex in particular exhibits a great deal of plasticity as a function of motor learning. Using transcranial magnetic stimulation, a number of investigations have mapped the degree and extent of excitability of individual muscles on the scalp surface. Body parts that are used more have a larger representation, and this representation shrinks if the body part is not used (see the study by Pascual-Leone et al.73). On the basis of neuroimaging paradigms, a variety of brain regions have been demonstrated to be active depending on the task and the stage of motor learning; in nearly all cases, however, there is activation of the primary motor cortex.75

In most neuroimaging studies, cerebellar activation is evident in the learning phase and declines when the movement is learned. This certainly indicates a role in learning and, in particular, suggests that the cerebellum may critical for developing the movement representation but not storing it. The frontal and parietal lobes are also clearly involved in motor learning, but the precise structures involved in early vs. later stages of learning are unclear. For example, a frontal-to-parietal shift in activation has been observed as a sequence task is learned,76 and a prefrontal-to-premotor, posterior parietal, and cerebellar shift in activation has been observed in force adaptation learning.77 On the other hand, several studies using motor sequence tasks and at least one using a rotational learning task have demonstrated that parietal activation is associated with early stages of learning, with greater cerebellar and/or premotor involvement in later stages.78–81 At this juncture, we may conclude that the parietal regions so frequently lesioned in apraxic patients are clearly important in aspects of skill learning.

There is evidence that perilesional plasticity may play a role in recovery of function after stroke. It has been shown, for example, that after finger tracking movements, paretic stroke patients improved in finger pointing accuracy and grasp and release capabilities.82 These functional gains were accompanied by increased functional magnetic resonance imaging activations in sensorimotor areas of the lesioned hemisphere and diminished activations in the intact hemisphere (see also Fridman et al.83).

At least one previous account has attributed preserved function in apraxia to preservation of nondominant (right)-hemisphere frontoparietal regions involved in praxis function.84 On the other hand, nondominant-hemisphere plasticity changes have been demonstrated to be maladaptive in recovery from aphasia,85 and they may plausibly be similarly counterproductive in apraxia recovery. Additional investigations are required to shed light on this question.

Implicit and Explicit Skill Learning

A considerable literature attests to important differences between skill learning that is unavailable to conscious experience (implicit learning) and that which is cognitively accessible. Ideally, the study of learning in apraxia could tap into this large body of evidence to support the framing of hypotheses and predictions. However, one critical concern is that it is not clear whether to align praxis learning with explicit or implicit knowledge, or both. The types of complex skills that fall under the rubric of praxis are not typically verbalized, yet they can be made explicit under certain circumstances. It is, perhaps, most reasonable to begin with the hypothesis that praxis learning is more similar to implicit procedural learning than to learning of declarative information. Specific investigations that test predicted patterns of results according to this hypothesis need to be performed.

A typical exploration of skill learning entails the use of serial reaction-time tasks. Participants are usually faster at performing sequences of key presses that are repeated throughout an experiment, even though they are unaware of the repetition. This is an example of implicit learning. With additional practice, the sequence can frequently be specified; in this case, the learned information has...
become declarative as well as procedural. Performance gets even better at this stage, but the subject’s strategy can change because the stimuli can be consciously anticipated.

Honda et al.\textsuperscript{86} examined the dynamic involvement of different brain regions in implicit and explicit motor sequence learning using a serial reaction-time task and positron emission tomography. During the implicit learning phase, when the subjects were not aware of the sequence, improvement of the reaction time was associated with increased activity in the contralateral primary sensorimotor cortex. Explicit learning, reflected by a positive correlation with correct recall of the sequence, was associated with increased activity in the posterior parietal, precuneus, and premotor cortices bilaterally; in the supplementary motor area, predominantly in the left-anterior part; in the left thalamus; and in the right-dorsolateral prefrontal cortex. In a study by Grafton et al.,\textsuperscript{87} there was activation of the contralateral primary motor cortex, supplementary motor area, and putamen in an implicit learning task, and activation of ipsilateral dorsolateral prefrontal cortex and premotor cortex as well as bilateral parietal cortex during explicit learning.

In summary of the studies of motor learning in healthy subjects, it seems that multiple structures in the brain are involved, and differential involvement arises at different stages. The primary motor cortex and cerebellum (and, sometimes, the parietal cortex) are active early, and at least the former seems to play a role in implicit learning. Premotor and parietal cortical areas are active later and seem to play a role in explicit learning, perhaps in part by storage of the sequence. This concept is supported by the observation that the premotor and parietal areas increase their activation in proportion to the length of a sequence performed from memory.\textsuperscript{88} The relation is obvious to regions that, when damaged, cause apraxia.

**PRINCIPLES OF MOTOR LEARNING AS THEY MAY BE RELEVANT TO APRAXIA REHABILITATION**

Several basic principles of motor learning have been explored in other aspects of motor control rehabilitation, but they have received relatively little attention in the study of IMA.

**Internal Models of Movement**

The motor system in healthy participants is adept at developing internal models that represent the kinematics (geometry and speed) and dynamics (forces) of a motor task. Forward models calculate the movements resulting from a given pattern of force (dynamics) or the limb positions resulting from a given pattern of joint rotation (kinematics). Inverse models compute the muscle forces or movements needed to reach a visual goal or goal posture.\textsuperscript{89} The learning (i.e., practice-dependent reduction of error) of kinematic and dynamic internal models seems to be separable, and it may be disrupted by different brain lesions.\textsuperscript{90}

Several models of motor performance distinguish a mode of action concerned with planning, learning, and motor prediction, and another specialized for motor execution and control (see Keele\textsuperscript{91}). One influential account distinguishes semantic representations necessary for motor learning and planning from pragmatic representations subserving the control and execution of action.\textsuperscript{92} The planning mode has been proposed to generate movement parameters by way of internal models. The execution mode, in contrast, emphasizes online control that is sensitive to current environmental conditions.

Recent investigations provide indirect evidence that patients with IMA may be impaired in learning and/or accessing internal models of movement. Motor imagery has been proposed by several investigators to serve as a proxy for motor planning in the absence of execution.\textsuperscript{93–97} Sirigu et al.\textsuperscript{98} and Buxbaum et al.\textsuperscript{25} have demonstrated that patients with left-parietal lesions and IMA were impaired in motor imagery. In contrast, these patients perform well on tasks more reliant on online control, such as reaching and grasping with visual feedback.\textsuperscript{13,26} The nature and extent of putative deficiencies in generating and accessing internal models are being explored in several of the authors’ laboratories, using visuomotor and force-field adaptation paradigms borrowed from the motor control literature. Such studies are an important step in developing rehabilitation paradigms targeted at the relearning of appropriate internal models.

**Practice Schedules**

It is clear that practice benefits motor learning, but optimal types and schedules of training remain unclear and may vary across tasks. In most motor tasks, practice that is distributed over (rather than massed in) time seems to result in optimized learning and retention.\textsuperscript{99} In learning new sensorimotor transformations, rest breaks between sessions are of benefit and may allow for the consolidation of newly acquired internal models.\textsuperscript{100} It is also frequently beneficial to train a variety of similar movements to encourage so-called contextual interference. Shea and Kohl,\textsuperscript{101} for example, found in a force-learning task that filling the inter-test-trial interval with related motor tasks significantly improved retention. Ollis et al.\textsuperscript{102} have demonstrated that learning a variety of knot-tying movements enhances learning, even for novices practicing complex knots. It has been suggested,
The Role of Feedback and Error Correction

Feedback and knowledge of results frequently facilitate motor skill acquisition. Recent investigations have probed the types of feedback that may be most optimal, and here, as in other areas of motor learning, the answer is unclear. For example, varying the movement component about which feedback is provided may benefit simple skill learning, but it may also disrupt more complex motor skill learning.107

In the domain of cognitive implicit learning, error may be disruptive. As a result, rehabilitation paradigms have evolved that emphasize errorless learning. Performance may be “shaped” by minimizing opportunities to make errors and by rewarding successful performance. In contrast, in the domain of simple movements, such as reaching under visual guidance, performance seems to be “tuned” by the opportunity to correct error (e.g., Rossetti et al.108). The role of error in these different types of learning remains poorly understood; moreover, it is not clear whether and where praxis movements may fall on this continuum.

Hemiparetic stroke patients without IMA are able to adapt to forces applied perpendicularly to the moving hemiparetic arm109 as well as to springlike forces that act against movement110 when they receive feedback about error. This suggests that hemiparetic patients can use error to adjust internal models of movement to achieve an intended goal.109,111 It has also been suggested that perception of gross errors may enhance the recovery process in stroke.112

Unfortunately, patients with apraxia frequently exhibit some degree of anosognosia, or unawareness of deficit. They may recognize that they are unable to move correctly, but they fail to recognize the extent of deficit, or they may attribute it to clumsiness, memory loss, or intellectual decline.113 It may be necessary to provide augmented feedback about error. Fortunately, a number of virtual-reality paradigms under recent development present promising opportunities to do just this (see Holden114).

Paradigms using robot-assisted devices115,116 can launch correct actions based on electromyographic activity that is associated with the intention to act. Thus, preparatory activity is linked to a correct response, and errors are prevented. This would seem to be an extremely useful feature. However, given that IMA patients may fail at the level of planning and intention, it is not obvious that robot-assisted therapies will be helpful in the rehabilitation of IMA, unless the correct performance of an act can feed back to augment the putatively deficient internal model.

SUMMARY AND RECOMMENDATIONS

There are several different subtypes of apraxia, resulting in some cases from damage to differing underlying neural systems. Ideomotor, ideational, and conceptual apraxia all seem to impact real-world functioning. Development of appropriate treatment paradigms is clearly needed. A review of the apraxia treatment literature to date reveals that the field is in the early stages of efforts to develop effective treatments and that most studies have relied on individual-case, experimental designs. Additional problems include poor specification of patient characteristics, including incidence of aphasias; variable criteria for diagnosing apraxia; vague description of treatments applied; unequal application of treatment, even within a given study; and absence of information about treatment generalization. Most central to the aims of this review, principles from the existing motor learning literature have not yet informed the development of treatment studies.

The motor learning literature identifies several principles that may benefit the rehabilitation of apraxia, if appropriately applied. For example, distributed practice of the target task seems to improve learning and retention. Creating contextual interference by interleaving the target task with other similar tasks may aid117 or disrupt (c.f. Plaut et al.106) generalization. Feedback of results should be provided. Intensity of practice is also clearly important.

One potential strategy in the development of apraxia treatment studies is to systematically vary one treatment feature at a time (e.g., massed vs. distributed practice schedule; similarity or distinctiveness of items; presence or absence of feedback; shaping of easier to harder items to maximize success, as opposed to allowing errors) while systematically holding the others constant. This is clearly preferable, from the perspective of clarifying the features of the training that are critical. On the other hand, there is, unfortunately, very little
to suggest how these motor learning principles are best parameterized (e.g., in terms of strength, duration, or intensity) or applied to the treatment of IMA. Another strategy, then, is to attempt to obtain a beneficial effect by “loading” the treatment on all of the motor learning features that may plausibly be beneficial, and, if an effect is obtained, follow up with studies designed to disentangle the critical vs. noncritical factors. Of course, if no training benefit is observed, then it would be unclear which features were applied incorrectly, and this, in turn, would necessitate a return to the “one feature at a time” strategy.

As an exercise, at least, we can imagine a treatment study based on the strategy of loading the treatment with principles derived from the motor learning literature. One might predict, for example, that deficits in naturalistic action may be most successfully treated by providing an intense but distributed schedule of practice on a variety of targeted naturalistic tasks, interleaved with other similar tasks. Principles of shaping might be predicted to be beneficial, such that easy tasks are used early in training and harder tasks later in training, such that performance is successful. On the other hand, opportunities to correct errors should be provided, should they arise.

The apraxia literature also provides some hints about other factors that may impact rehabilitation. A recent learning study from the lab of one of the authors has assessed the role of the affordances of unfamiliar objects—in this case, the degree to which the unfamiliar objects signal the actions associated with them by virtue of their shape—in learning new, object-related gestures. Patients with IMA, but not age- and education-matched nonapraxic left-hemisphere stroke patients, were significantly better at learning new gestures when the gestures were associated with them by virtue of their shape—in learning new gestures. This affordance benefit could clearly be exploited in the design of future treatment studies by focusing early treatment on high-affordance objects.

Tasks trained early in a shaping procedure may be designed to be “easy” in a number of other critical ways. Clearly, these early tasks should have a few steps. Arrays should be simple, with few visual elements, and no distracting (task-irrelevant) objects. Spatial consistency of object placement from trial to trial is also critical. These task and object features may all be titrated gradually, such that tasks higher up in the shaping hierarchy are increasingly complex with respect to these features.

Treatments must be applied identically across all treated subjects. Treated and untreated patients must either be matched across a large number of putatively important variables—including lesion size, severity of cognitive and language deficits, apraxia type (and subtype) and severity, and motor impairment—or sample sizes must be large and patients randomly assigned to treated and untreated groups. Efficacy of treatment should be assessed by applying pre- and posttreatment measures of caregiver burden, performance of ADLs, and/or functional independence that are different from the trained tasks.

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