Treatment of Limb Apraxia: Moving Forward to Improved Action

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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
Introduction

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) as compared with less-practiced movements. Although several types of apraxia have clear impact upon 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 rehabilitation of limb apraxia, and based on the learning and plasticity literature, generate suggestions for how translational principles might be applied to guide future treatment research.

Definitions of apraxia

The term ‘apraxia’ was introduced by Steinthal. While this word is derived from Greek and literally means without action, the term apraxia is used 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. Liepmann described three forms of apraxia which, 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 Rothi, Heilman, Ochipa and colleagues \textsuperscript{5-7} added another type, termed conceptual apraxia, and DeRenzi as well as Heilman \textsuperscript{8, 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’s 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 upon imitation of others \textsuperscript{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 \textsuperscript{13}. Spatiotemporal errors persist to a lesser degree with actual tool use \textsuperscript{15, 16}. The deficit is not restricted to meaningful movements, and has also been observed in meaningless postures \textsuperscript{17-19} and sequences \textsuperscript{20, 21}. IMA is also associated with cognitive deficits in declarative knowledge of the action appropriate to objects \textsuperscript{22}, impairments in mechanical problem-solving \textsuperscript{23}, deficits in motor planning \textsuperscript{21, 24-26}, and difficulty learning new gestures \textsuperscript{27, 28}. Testing for IMA frequently includes pantomiming to command of transitive (familiar actions with objects, e.g., brush teeth) and intransitive (symbolic movements without objects, e.g., 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 upon which tools act.

Several investigators have distinguished between IMA with impaired gesture recognition (“representational” IMA) and IMA with intact recognition (“dynamic” IMA; 11, 29, 30). In representational IMA, inability to discriminate correctly from incorrectly performed meaningful object related hand movements correlates strongly with 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, who wrote, “…apraxia rarely appears in everyday situations and spontaneous motor behaviour, predominantly emerging when gestures are produced out of context as a purposeful response to an artificial request.” Although not specified, it appears 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 are fraught with problems. First, these studies usually do not rule out the
influence of all other factors, such as hemiparesis. They commonly compare the performance of apraxic and nonapraxic patients with left hemisphere damage\textsuperscript{36-41}, but relative to nonapraxics, apraxics are often more impaired in other domains, such as language and sensory and motor skills. Therefore, it is difficult to know if limb apraxia is the best predictor of functional skills. Second, apraxics typically have larger lesions than patients without apraxia, and those lesions more frequently damage the left parietal and frontal regions\textsuperscript{42} that are also important for many other cognitive functions that could again confound the findings. Regression approaches have been used in order to evaluate the unique impact of various factors including limb apraxia on activities of daily living\textsuperscript{41}, \textsuperscript{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 suffer 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 is the use of a wide variety of functional measures, including object use\textsuperscript{46, 47}, performance-based measures of activities of daily living\textsuperscript{36, 37, 39, 41, 43, 48, 49}, and caregiver or patient report of daily functioning\textsuperscript{39, 44, 45, 50}. These outcome measures vary in complexity from isolated object use, such as brushing teeth\textsuperscript{51}, to simulated activities of daily living, such as picking up a bean with a spoon\textsuperscript{38, 39, 41}, to instrumental activities of daily living, such as eating a meal\textsuperscript{36}, dressing\textsuperscript{49, 52}, preparing food\textsuperscript{43, 48, 53-55} or changing batteries in a recorder\textsuperscript{37}. It is common in performance-based studies to use instruments that do not have demonstrated reliability; thus, validity is frequently demonstrated only in the context of the specific study. In addition, there are significant problems with obtaining
reliable measures of these skills because the tasks are usually quite complex and the number of possible errors is large. Furthermore, because performance-based tasks are dependent upon a great number of cognitive abilities, patients may be impaired for different reasons 56, 57.

Taken together, these problems in the literature suggest that future studies must 1) examine the relationship of different types of limb apraxia to real world functioning (activities of daily living and instrumental activities) of various kinds; and 2) utilize sufficiently large groups of patients to provide sufficient power for analysis. It is also reasonable to consider at least two different approaches for subject recruitment. The first approach examines well-characterized patients with unilateral focal lesions, and the second approach examines a broader range of patients with and without limb apraxia without regard to lesion location. The latter approach may yield patients more broadly representative of the patients typically seen in the clinic.

Finally, some of the most innovative work in this area attempts to identify cognitive mechanisms that are associated with ideomotor limb apraxia and potentially with the resulting deficits in real world functioning (see 58 for a review). These cognitive processes include mechanical problem solving 46, sequence planning and organization 21, the ability to develop and/or retrieve optimal motor programs 13, knowledge of how to manipulate an object 22, 25, 59, and knowledge of optimal hand position when real world objects provide minimal cues 25, 39.
Treatment of Limb Apraxia

A recent review of the literature on 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, Rothi & Greenwald\(^6\) for a 55 year 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 one hour sessions daily for two weeks. 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\(^6,62\) conducted a treatment study aimed at treating specific error types. Two males, 44 and 66 years old, with chronic Broca’s aphasia and ideomotor apraxia but preserved gestural recognition participated in the treatment. Treatment duration and intensity varied, with the 44 year old receiving treatment four times per week (n=44 sessions) and the 66 year 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 upon the error types exhibited by the individual. Reduction of external configuration errors involved training the individual to correctly orient his hand to objects, while reduction of internal
configuration errors involved positioning of 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 2 week post treatment follow-up, but later follow-ups were not performed.

**Six Stage Task Hierarchy.** The task hierarchy method was developed by Code & Gaunt who studied in 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 for treatment of apraxia of speech. The Code and Gaunt method involves requiring the patient to produce target words and signs in various combinations and in concert with the therapist in response to a therapist model or in response to a picture elicitation. The patient participated in 45 minute sessions once weekly for 8 months. The six stage task hierarchy method resulted in acquisition of trained signs and a non-significant 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 & Humphreys for a patient with head injury and chronic unimanual apraxia of the non-dominant 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 minute sessions for 3 weeks. The conductive education method
improved this patient’s performance on treated items as compared to untreated items.
There was no generalization to untreated objects. Maintenance of effects were not
assessed.

Strategy Training. The strategy training method was developed as a compensatory
technique for individuals with ADL (Activities of Daily Living) 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 66. The patients were trained on three
ADLs, and the specific method of treatment was chosen based on each individual’s
performance in baseline testing of those tasks. A similar strategy training method
utilizing 5ADLs 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 (ie, self-verbalization) and external compensatory
strategies (ie, 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 .37 for the ADL tasks and .47 for the
Barthel ADL index; both significantly greater than for patients receiving usual
occupational therapy treatment), but the improvements were not lasting 67,68. In the final
study in this series, there was an additional finding of interest; namely, maintenance of
gains in trained tasks at 5-month followup.  

Transitive/Intransitive Gesture Training.
The transitive/intransitive gesture training method was investigated by Smania and colleagues in 22 individuals at least two months post 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 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 related symbolic gesture, and asked to reproduce the gesture (2) shown the context picture alone, and asked to reproduce the gesture (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 weeks, with the number of total treatment sessions ranging from 30-35. A control group was administered aphasia treatment only for a similar intensity and duration. Results indicated there was a difference between the two groups post-treatment, with the gesture training method resulting in improved performance on an IMA test (U=69.00, p=.016), a gesture comprehension test (U=64.00, p=.018) and an ADL questionnaire (U=53.50, p<.01). Importantly, patients and caregivers reported more independence in ADLs following treatment. Nine patients showed maintenance of gains at two months post 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 in order to teach patients how to produce the same gesture under
different contextual situations” (p. 2052). Thus, although details were not provided, the
treatment appears substantially similar to the one previously reported by this group 69.
Forty-one post-acute 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. Patients attended 30 fifty-minute sessions
over the course of 10 weeks. Although the groups were equivalent in ADL performance,
apraxia scores, and ADL questionnaire scores prior to treatment, they differed
significantly on these measures after treatment, both immediately and after a 2 week
delay.

Errorless Completion + Exploration Training. The errorless completion/exploration
training method was developed by Goldenberg & Hagmann 51 for 15 individuals with
IMA (impairment on gesture imitation and gesture to sight of objects) who were on
average 6.1 weeks post onset of a left hemisphere stroke with subsequent aphasia and
severe limb apraxia. The errorless completion method utilized 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 minutes for 2-5 weeks. 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, Daumuller, &
Hagmann comparing these two methods in 6 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 to untrained gestures. Therefore, there was no evidence of generalization.

Table 1 about here

Table 1 provides a summary of the 10 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, while some studies provide data on treatment effects and generalization to untreated items, they are more sparse with regards to treatment effect upon degree or nature of limb apraxia, maintenance of treatment effect, and impact of treatment upon 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 upon 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 upon nature/degree of limb apraxia as well as upon ADL facility. Thus, it appears that the evidence based on these 10 Phase I studies suggests that limb apraxia is amenable to treatment. However, according to Robey \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 10 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 9 of the 10 treatments reported in the literature yielded a treatment effect. However, only 4 of these 9 treatments resulted in generalization. Since 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 while others did not.

Nadeau et al \textsuperscript{72} recently 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; 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 4 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 while others did not. Of the 3 treatments that incorporated home practice (contextual mechanism), none resulted in generalization. In addition, based on the available information, there appears to be no consistent relationship between duration/intensity/type of items trained and generalization of results. These equivocal results suggest that while limb apraxia may be amenable to treatment, systematic investigation of factors promoting generalization is still essential.

**Motor Learning and Motor Plasticity: An Overview**

The learning of skilled movements is called procedural learning, and its underlying mechanisms and neuroanatomical correlates differ from declarative learning\(^73\). In the following sections, we will provide a brief introduction to the literature on motor learning and plasticity, with an eye 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 (e.g., 74). Based on 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 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 be 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 versus 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, 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 fMRI activations in sensorimotor areas of the lesioned hemisphere, and diminished activations in the intact hemisphere (and see\(^{83}\)).

At least one previous account has attributed preserved function in apraxia to preservation of non-dominant (right) hemisphere fronto-parietal regions involved in praxis function\(^{84}\). On the other hand, non-dominant hemisphere plasticity changes have been demonstrated to be maladaptive in recovery from aphasia\(^{85}\), and 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 based on this hypothesis need to be performed.

A typical exploration of skill learning entails the use of serial reaction time tasks (SSRT). Participants are usually faster to perform sequences of key presses that are repeated throughout and 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 since 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 SRTT 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, supplementary motor area predominantly in the left anterior part, left thalamus, and 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 appears that multiple structures in the brain are involved, and that differential involvement arises at different stages. The primary motor cortex and cerebellum (and sometimes parietal cortex) are active early and at least the former appears to play a role in implicit learning. Premotor and parietal cortical areas are active later and appear 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. The relation to regions that when damaged cause apraxia is obvious.

**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 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. The learning (that is, practice-dependent reduction of error) of kinematic and dynamic internal models appears to be separable, and may be disrupted by different brain lesions.

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 91). One influential account, for example, distinguishes semantic representations necessary for motor learning and planning from pragmatic representations subserving the control and execution of action 92. The planning mode has been proposed to generate movement parameters by way of internal models. The execution mode, in contrast, emphasizes on-line 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 93-97. Sirigu et al. 98 and Buxbaum, Johnson-Frey, & Bartlett-Williams 25 demonstrated that participants with left parietal lesions and IMA were impaired in motor imagery. In contrast, these patients perform well on tasks more reliant upon on-line control, such as reaching and grasping with visual feedback 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 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 appears to result in optimized learning and retention 99. In learning new sensorimotor transformations, rest breaks between sessions is 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 & 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} demonstrated that learning a variety of knot-tying movements enhances learning, even for novices practicing complex knots. There is some suggestion, however, that the benefit of contextual interference may be task specific\textsuperscript{103}. Additionally, a contextual interference manipulation in patients with Parkinson’s disease did not enhance learning, suggesting that successful learning strategies in healthy controls may not generalize to brain-damaged patients\textsuperscript{104}. It is also of interest to note that training of items that share many features with other items is disruptive and not beneficial in the lexical-semantic domain\textsuperscript{105,106}. As object-related praxis movements are complex skills with close ties to semantic knowledge\textsuperscript{22}, it remains unclear whether training on shared or distinctive motor features, semantic features, or both will be optimal in praxis rehabilitation.

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 disrupt more complex motor skill learning\textsuperscript{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 appears to be “tuned” by the opportunity to correct error (e.g., \(^\text{108}\)). 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 perpendicular to the moving hemiparetic arm \(^\text{109}\) as well as to spring-like forces that act against movement \(^\text{110}\) 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 \(^\text{109, 111}\). It has also been suggested that perception of gross errors may enhance the recovery process in stroke \(^\text{112}\).

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 fail to recognize the extent of deficit, or may attribute it to clumsiness, memory loss, or intellectual decline \(^\text{113}\). 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 \(^\text{114}\)).

Paradigms using robot-assisted devices (e.g., \(^\text{115, 116}\)) 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.

V. 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 appear 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 upon individual case experimental designs. Additional problems include poor specification of patient characteristics, including incidence and of aphasia, 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 appears to improve learning and retention. Creating contextual interference by interleaving the target task with other similar tasks may aid or disrupt (c.f. 106) generalization. Feedback of results should be provided. Intensity of practice is also clearly important.

One potential strategy in development of apraxia treatment studies is to systematically vary one treatment feature at a time (e.g., massed versus 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 versus non-critical 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 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 non-apraxic left hemisphere stroke patients, were significantly better at learning new gestures when the gestures were highly afforded by their associated objects. 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 few steps. Arrays should be simple, with few visual elements, and no distractor (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 post-treatment measures of caregiver burden, performance of ADLs, and/or functional independence that are different from the trained tasks.
ACKNOWLEDGMENTS

This paper is an outgrowth of a Workshop in Plasticity/NeuroRehabilitation Research sponsored and supported by the VA Brain Rehabilitation Research Center of Excellence and the University of Florida Dept. of Occupational Therapy, Gainesville, Florida. Work on the manuscript was supported in part by NIH R01-NS036387 to the first author.
REFERENCES


### Table 1: Summary of Apraxia Treatment Studies

<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>Multi Cues (n=1)</td>
<td>IMA gestures</td>
<td>2 weeks</td>
<td>1 hour daily</td>
<td>Y</td>
<td>Y</td>
<td>Y-treatment items only (2 weeks)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Error Type Reduction (n=2)</td>
<td>IMA gestures</td>
<td>Varied; 6-11 weeks</td>
<td>Varied; once daily 4 days/week- twice daily 2 days/week</td>
<td>Y</td>
<td>N</td>
<td>Y-treatment error types only (2 weeks)</td>
<td>N</td>
<td>NA</td>
</tr>
<tr>
<td>Six Stage Task Hierarchy (n=1)</td>
<td>IMA + IA gestures</td>
<td>8 months</td>
<td>45 minutes; once weekly</td>
<td>Y</td>
<td>N</td>
<td>NA</td>
<td>N</td>
<td>NA</td>
</tr>
<tr>
<td>Conductive Education (n=1)</td>
<td>IMA gestures</td>
<td>3 weeks</td>
<td>Daily</td>
<td>Y</td>
<td>N</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Strategy Training (n=89)</td>
<td>IA?* ADL</td>
<td>Varied; 8-12 weeks</td>
<td>Varied; 25 sessions, 15 hours total</td>
<td>Y</td>
<td>Y</td>
<td>N (5 months)</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Transitive/Intransitive Gesture Training (n=13)</td>
<td>IMA gestures</td>
<td>10-11 weeks</td>
<td>35 sessions, 50 minutes each</td>
<td>Y</td>
<td>Y</td>
<td>NA</td>
<td>Y</td>
<td>NA</td>
</tr>
<tr>
<td>“Rehabilitative Treatment” (n=20)</td>
<td>IA or IMA gestures</td>
<td>10 weeks</td>
<td>30 sessions, 50 minutes each</td>
<td>Y</td>
<td>Y</td>
<td>Y (2 weeks)</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Errorless Completion + Exploration Training (n=15)</td>
<td>NA ADL</td>
<td>2-5 weeks</td>
<td>5 days/week plus 20-40 minutes practice daily</td>
<td>Y</td>
<td>N</td>
<td>Y (6-30 months)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Errorless Completion (n=6)</td>
<td>IMA ADL</td>
<td>2 weeks</td>
<td>6 sessions, one hour each</td>
<td>Y</td>
<td>N</td>
<td>Y (3 months)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Exploration Training (n=6)</td>
<td>IMA ADL</td>
<td>2 weeks</td>
<td>6 sessions, one hour each</td>
<td>N</td>
<td>N</td>
<td>Y (3 months)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Legend: IMA = ideomotor apraxia, IA = ideational apraxia, Y = yes, N = no, NA = not assessed/no information provided
* “Inability to carry out purposeful activities”