Integrating Motor Control and Motor Learning Concepts With Neuropsychological Perspectives on Apraxia and Developmental Dyspraxia

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This paper reviews selected pertinent literature on the learning and performance of skilled motor acts. Information on normal motor performance is integrated with that on adult apraxia and related to common problems observed in children with developmental dyspraxia. The process of motor skill acquisition is outlined, and aspects of styles of motor organization, modes of control, premovement organization, sensory organization, and analysis of the types of errors are presented. Recommendations for clinicians working with children with developmental dyspraxia are offered.

Problems in motor planning, clumsiness in execution, inappropriate actions, and difficulty in motor learning have been associated with apraxia in adults and developmental dyspraxia in children. Separate terms for adults and children are used to describe a disturbance of praxis—the ability to plan and execute a skilled movement—because the etiology and neurophysiology, behavioral manifestations, and evaluation and treatment of problems in praxis differ for the two groups. Previously, most studies of apraxia have focused on neuroanatomical correlates of defective motor actions (Geschwind, 1975; Heilman, 1979; Luria, 1963) and the classification and description of apraxia in adults and children (Ayres, 1972, 1975, 1985; Cermak, 1985; Conrad, Cermak, & Drake, 1984; Geschwind, 1975; Gubbay, 1975, 1979; Hecaen, 1968; Hecaen & Albert, 1978). From another perspective, motor learning theorists have primarily investigated the construct and content of motor programs and the stages and strategies of motor learning (Fitts & Posner, 1967; Goodman & Kelso, 1980; Rosenbaum, 1980; Schmidt, 1975, 1988; Singer, 1978).

An Integrated Typology of Apraxia

Integrating literature from motor learning and neuropsychology, Roy (1978) developed a typology of apraxia in adults that incorporated the identification of neural substrates associated with specific defects and the underlying behavioral processes involved in motor skill acquisition and normal motor control. Roy described apraxia as a disturbance to a complex functional system and classified it in terms of the two basic functional processes affected: planning and execution. From these two disorders, Roy identified three types of apraxia: (a) planning apraxia with two subcategories—primary and secondary planning apraxia; (b) execution apraxia; and (c) unit apraxia. Defects in primary planning apraxia are manifested by disturbances in the ability to conceptually organize the requisite movement sequence and a general cognitive organizational disorder not restricted to motor behavior. Roy correlated this disorder with frontal lobe pa.
Motor Action Problems in Developmental Dyspraxia

Clinically, we have found that, although specific symptoms vary, children with developmental dyspraxia appear to share some common problems, including an impaired ability (a) to learn general rules or schemata about classes of motor actions, (b) to use appropriate perceptual cues (e.g., spatial location, object speed or trajectory) within their environmental context, (c) to organize and integrate information from the body senses (e.g., somatosensory, vestibular), (d) to solve problems and adapt behavior to new or unexpected situational demands, (e) to analyze task requirements and components, (f) to effectively use knowledge of performance for upcoming actions, and (g) to prepare for upcoming actions.

Children with developmental dyspraxia seem to be able to understand the goal of the motor action but are not able to effectively plan and execute new motor actions or generalize learned motor actions in new situations (Ayres, 1975, 1985; Kephart, 1971). They have difficulty understanding the relationship between similar motor actions, particularly when adaptive or problem-solving behaviors are required. Often, these children appear out of sync with their environment, that is, their timing is off or their response is out of proportion; they do not appear to meet the specific demands or conditions of the task. This is due perhaps to a problem these children have with organizing sensory input, efficiently identifying the most relevant and minimal cues or environmental stimuli, or integrating their actions with these cues (Singer, 1978). For example, the child may swing a bat only after the ball has passed the plate. This may occur because the child is attending to the person throwing the ball or to specific characteristics of the ball itself (e.g., color, shape) rather than to the speed of the ball or the angle of the trajectory, or the child may not take his or her movement time into consideration when initiating the action.

Children with developmental dyspraxia can usually assess whether or not they have successfully completed the goal of motor action. They often have difficulty, however, with attributing performance out-
comes to the appropriate reason. That is, they cannot analyze the task demands and task components and are, therefore, ineffective in using knowledge of performance feedback (Gonzalez-Rothi & Heilman, 1985).

Additionally, children with developmental dyspraxia often do not appear ready for upcoming actions. Before one takes an action there is normally a postural biasing of the muscles that are not the primary movers in the action (e.g., before throwing a ball, the muscles of the trunk will be activated). These postural movements are in anticipation of perturbations associated with the given action. This is known as premovement organization, postural biasing, or preturning and is a critical component of the motor action system (Lee, 1980). The premovement organization not only provides improved overall equilibrium of the system but also is thought to improve execution of the action by constraining degrees of freedom (Kelso, 1982). For example, if the child is not ready for the upcoming motor actions associated with swinging a bat, postural responses to the change in the center of gravity may be delayed or excessive, thereby causing a loss of standing balance.

An understanding of the nature of developmental dyspraxia requires a full understanding of the phases of motor skill acquisition as well as of the motor action system, including styles of motor organization, modes of control, premovement organization, and sensory organization.

Motor Skill Acquisition

Motor skill acquisition has been described as proceeding through three phases (Fitts & Posner, 1967). In the first phase, called the cognitive or early phase, the learner establishes a general understanding of the task and develops a cognitive map of the movements most likely to accomplish the goal. Nonmotor aspects of the task are learned. Fitts and Posner (1967) suggested that early motor learning is primarily under visual control. The second phase, called the associated or intermediate phase, is described as a period of modularization (the process of increasing efficiency and decreasing variability) in which movement patterns become more coordinated in regard to spatiotemporal organization. Proprioceptive feedback is thought to become increasingly important, allowing a gradual decrease in reliance on visual cues. The final phase in motor learning, the autonomous phase, is characterized by the development of larger functional units, translated into a motor program, which occurs with minimal conscious attention. At this stage, the performer can attain a state of readiness and can anticipate environmental changes. Cognitive regulation is minimized and conscious introspection regarding the components of the pattern can interfere with performance at this phase. Temporal organization (timing) is identified as the last aspect of the autonomous phase to be fully organized and remains the most easily disturbed. Although identification of the sequence of these stages is helpful for understanding skill learning, the process itself may be discontinuous, occurring in spurts and plateaus. Further, Fitts and Posner viewed their model as applicable to all motor learning, and they did not specifically consider the person's age or experience.

Singer (1978), focusing on the importance of cognition to learning and to the performance of perceptual-motor tasks, described three elements of cognition in motor skill acquisition: (a) goal image formation, in which the learner creates an image of what an action encompasses; (b) goal expectancy formation, in which the learner develops performance expectations based on past successes or failures; and (c) direction and control of the act, which guides the plan of the action. Singer also emphasized the importance of the maintenance of optimal arousal and motivational states during motor learning. Singer suggested that cognition in the form of rules, strategies, plans, and the formation of programs assists the production of skilled movement. In turn, skilled movement is the combined result of the elements of cognition, the response repertoire (i.e., experience), and the resources of the physical system. Singer cautioned that the training and learning of cognitive strategies must be based on task classification and the skill level of the performer as well as on other individual differences.

A discussion of motor skill acquisition should also include the development of motor programs. For example, what does it mean to modularize or to develop a motor program? How is the process fostered? Theories of motor programming remain speculative and controversial (Schmidt, 1982; Zaichkowsky & Fuchs, 1986). Currently, a motor program is thought to be a generalized program that contains an abstract code regarding a class of movements with a common motor pattern, such as throwing. By changing response specifications, for example, the speed or force of the throw, the performer can change the performance outcome. Generalizations or schemata are thought to develop through practice as the performer learns the rules governing that set of movements, but the theories do not explain how the motor programs are learned or selected (Shapiro & Schmidt, 1982). More research is needed in this area. A better understanding of how these rules are learned and how the movement sequence and phasing (timing) changes with practice would provide insight into the problems seen in children with developmental dyspraxia. It is beyond the scope of
this paper to present various viewpoints of the construct and content of motor programs by such theorists as Adams (1971), Bernstein (1967), Grillner (1975), Polit and Bizzi (1979), Schmidt (1975), and Kelso (1982). We instead recommend excellent reviews of this literature by Schmidt (1988), Shapiro and Schmidt (1982), and Zaichkowsky and Fuchs (1986).

The Motor Action System

Styles of Motor Organization

In 1978, Roy stated that the behavior exhibited by patients with apraxia provided evidence for a hierarchical organization of motor control. Roy associated planning apraxia with a dissolution of the decision and perceptual processes involved in planning future motor actions and suggested that the motor plan is the summit of a vertical hierarchy. He based his perspective on motor skill models developed by Marteniuk (1976), Luria (1966, 1973), and Geschwind (1975).

More recently, Roy (1982) noted limitations in the ability of a hierarchical model to explain motor behaviors. Instead, he suggested that actions may be the outcome of a "non-linear heterarchy," that is, the interaction of a multiple component system in which motor actions can be directed or guided in a top-down or bottom-up fashion. Roy (1983) and Roy and Square (1985) promoted the distinction between a conceptual system, which provides an abstract representation of an action, and a production system, which generates the action. The former incorporates knowledge of objects, actions, and seriation of single actions into a sequence (i.e., parts of action into a complex whole) and is comparable to Singer's (1978) view of the importance of cognition in skilled movement. The conceptual system can control in a top-down fashion during learning, because the specific stored knowledge may be important in directing the production system. Conversely, in a bottom-up control mode, the environment sets constraints on movement and plays a role in directing the production system. Roy (1983) proposed that subcortical mechanisms may provide the neural basis interfacing the action system and the environmental demands during this data-driven, or bottom-up, control mode. He suggested that, in the bottom-up mode, there appears to be little conscious attentional demand. Roy (1983) also proposed that apraxic disorders can arise from a disruption in either the conceptual or production system. Disorders of the conceptual system are exemplified when the person knows the goal of the action or the object's use but uses his body part as the object (e.g., when demonstrating how to brush one's teeth, the finger takes on the properties of the toothbrush) or is unable to select the movements required to complete the action or to arrange the movements into the appropriate sequence. Disorders of the production system are exemplified by clumsiness, improper spatial orientation of objects and movements, and incorrect actions similar to the intended actions and perseverations.

On the basis of the earlier work of Bernstein (1967), Kelso and colleagues (Kelso & Tuller, 1981; Turvey, Fitch, & Tuller, 1982a, 1982b, 1982c) proposed a coalitional style of organization of the motor system in which actions are considered within their context, assuming a mutual compatibility between the person and the environment. Kelso and Tuller viewed apraxia as a breakdown in the synergistic relationship between the person, the activity, and the environment, as defined by the action goal. Additionally, they suggested that the requirements of the intended movement, which they referred to as the boundary constraints, specify necessary postural adjustments. This, they believed, decreases the number of degrees of freedom (decision possibilities) requiring control and thereby decreases the problem of too many unconstrained degrees of freedom.

Modes of Control

Open-loop and closed-loop modes of control of voluntary movement have received much attention over the past decade (Schmidt, 1975, 1988). Originally, the debate involved extreme viewpoints that hypothesized that control was only under one mode. The closed-loop mode, or inflow model, emphasized the role of feedback and attention, whereas the open-loop mode, or outflow model, involved a motor program or preplanned sequence of actions that could be executed without feedback and that allowed performance of the action without conscious attention. More recently, experimental evidence has supported the theory that the performer can switch between modes and that with specific actions and under specific conditions, one mode may become more advantageous than another (Notterman & Tufano, 1980). Moreover, the mode of control is often specified by the state of proficiency (learning), whether it is a new or a habitual skill.

Early in motor learning, the performer often relies more on sensory feedback by closely monitoring performance throughout the activity. As skill develops, feedback requirements may not only lessen, but also may change. Proprioceptive and kinesthetic feedback may be relied on more than visual input (Fitts & Posner, 1967). The overall cognitive strategy of how the performer uses sensory information may change as one becomes more proficient. Developmental changes in cognitive strategy are documented with maturation and experience, but the sequence of
those changes is not well defined (Goodgold-Edwards, 1984). Most of the literature discusses strategy changes in terms of information processing capabilities. For example, Hay (1981) investigated developmental changes in the information capacity of the motor system during a serial tapping task. This task required that the subjects tap reciprocally between two circles; target size and distance between targets were systematically varied. Performance improved with age, and superior performance was associated with vision directed toward one target with only periodic visual monitoring of the hand toward the other target. Similar ocular strategies were reported in another study (Connolly, Brown, & Bassett, 1968), and the authors suggested that the older children appeared to regard the task as a whole rather than as repeated discrete movements. Thomas (1980) proposed that with maturation and experience, the same amount of information can be processed in less time, more information can be processed simultaneously, and children can shift attention more easily during a task. He also suggested that retention capacity increases so that the child is less dependent on feedback and has less need for continuous self-monitoring.

Problems seen in children with developmental dyspraxia may, in part, be related to the allocation of attention and the use of feedback. Skilled motor behavior requires a delicate balance between open and closed modes of control. Roy (1982) described critical choice points when the performer may need to decide between two or more alternate choices of action. Thus, problems can arise when there is inaccurate attention or when the performer relies too heavily on one mode of control. If the child with dyspraxia remains in an early phase of motor learning using a closed-loop mode of control, then one can expect the child to display slow, jerky, or inaccurate movements or an inaccurate anticipation of future movements.

Premovement Organization

Postural biasing has been reported to occur not only during the performance of motor tasks but also before the performance of volitional motor tasks (Frank, 1971; Kelso & Tuller, 1981; Lee, 1980). For example, as stated previously in this paper, activity of the trunk musculature has been noted prior to the throwing of a ball. Current theories of postural control, therefore, include premovement organization in the form of movements that facilitate the coordination of posture and balance (Schmidt, 1988; Zaichkowsky & Fuchs, 1986). Postural mechanisms during volitional activities are thought to be determined before the movement and are based on experience. Premovement organization may help to constrain the number of degrees of freedom so that the performer has fewer decisions to make. Trunk musculature is activated in preparation for the changes in the center of gravity associated with the requisite arm action. Motor neuron pool sensitivity (activity level) has also been reported to increase before an action is taken, and Frank (1971) suggested that this helps ready the motor system for the upcoming movements.

Problems in execution of a volitional movement may be related to a disruption in premovement organization. The child with developmental dyspraxia who does not know the task requirements or movement sequence may not bias and ready the motor system for the upcoming actions. Without pretoning, the performer would have to rely on postural mechanisms triggered by feedback from perturbations. A loss of constraint of the degrees of freedom that are normally reduced by premovement organization could also result, so that the child is faced with more decisions.

Sensory Organization

Nashner (1982) has identified two major processes of postural and movement control: sensory organization, which integrates orientation information from visual, vestibular, and somatosensory input, and muscle coordination, which determines the temporal sequencing and distribution of muscle contractile activity. Postural control is context dependent, and the performer must select the most functionally appropriate information and use this knowledge before the action. Nashner suggested that the performer, rather than reacting to the changes in the environment after they occur, plans an action before the movement, based on assumptions about how the environment is structured (e.g., rough or smooth terrain, stable or unstable surface). Nashner and Shumway-Cook (1986) suggested that sensory organization must be flexible and adaptable. At different times, the same response may result from various sensory inputs, or one sensory input may cause various motor outputs. The response is dependent, in part, on the environmental context. Under normal circumstances, we rely on cross-modal sensations for balance. Information relating object to object through the visual system, self to earth through the vestibular system, self to self through the proprioceptive system, and self to object through the somatosensory system must be dynamically integrated. The different stimuli need to be unified into a complex whole, and those inputs that are useful, given the situation, need to be selected (Nashner & Shumway-Cook, 1986). Problems arise from an inappropriate selection of the postural movement strategy due to an inability to sense information or an inability to anticipate changes or a disruption of the muscle contraction patterns (e.g., relative ampli-
tudes, sequence, incorrect muscle contracting). The child with developmental dyspraxia may have a problem correctly integrating the body senses or selecting the most functionally appropriate sensory information or may have a problem interpreting the requirements of the task in regard to the environmental context.

Ayres (1985) believed that a sensory integrative deficit is a major contributor to developmental dyspraxia. She asserted that the brain must have various kinds of information to enable it to develop an adequate body scheme needed for motor planning. In addition to the idea of the purposeful act and the ability to conceptualize the action and its goal, the brain must know how the body is designed and how it functions as a mechanical being. That information comes from the visual, tactile, kinesthetic, proprioceptive, and vestibular systems. On the basis of a series of factor analytic studies, Ayres (1985) found a consistent relationship between dyspraxia and the tactile system and suggested that integration of somatosensory input is critical for the formation of adequate body scheme, which is needed for motor planning.

Errors in Normal and Pathological Populations

Another way of analyzing apraxia involves an analysis of the nature of errors and a comparison of errors produced by normal and pathological populations. This may provide insights into the processes and organization of the human action system. Roy (1982, 1983) and Roy and Square (1985) described three major types of errors in normal populations. The first occurs due to faulty analysis or discrimination of the required action (e.g., replacing the lid of a sugar container on a coffee cup), whereas the second type involves data-driven errors because the environment or stimulus precipitates the intrusion of an error (e.g., when driving to the movies, inadvertently turning down the street toward work). The third type of error is described as a misordering of the elements of a sequence or the false triggering of an action (e.g., while running water into a pot, putting the lid on the pot before turning off the water).

Roy (1982, 1983) and Roy and Square (1985) also described three major types of errors occurring in pathology. The first is a disorder in the actual performance of the action. Errors are characterized as disturbances to the order of the movement sequence, for example, omissions, repetitions, difficulty in terminating movements when required, and difficulty in coordinating the limbs in time and space. Errors of this type may include perseverations, may affect fine finger control, or may result in clumsiness. The second major type of pathological error is inappropriate actions that are performed correctly but that do not meet the immediate situation. These are considered context-dependent, or data-driven, errors. The patient may use an object or tool in an inappropriate way, such as using a pencil as a comb. Although the action of combing is correctly performed, it is performed with the wrong implement. The final type of pathological error is exemplified by complete omissions of the action. In this category, Roy (1982, 1983) and Roy and Square (1985) included situations in which a person (a) forgets what action he or she was about to perform, (b) is aware of what to do with an object but cannot demonstrate how to use it and may resort to deictic behavior (e.g., pointing to the location where the action takes place) or may use part as object behaviors, and (c) is aware of what to do and can describe how to perform the action but cannot initiate the action on command.

In comparing errors between persons without pathology and those with pathology, Roy (1982, 1983) and Roy and Square (1985) noted some commonalities, but stated that errors in perseveration or problems in the initiation of movements occur more frequently in pathology. In addition, they reported that the actual control of the action is rarely affected in normal persons. Furthermore, Roy (1982, 1983) suggested that the patient with apraxia may make data-driven errors due to an exaggerated context dependency on cues in the environment or, conversely, may be highly distracted due to an increased susceptibility to the environment. Because the motor action system uses environmental stimuli to perform skillfully, attention to wrong cues or to less salient cues interferes with the action. Thus, we must further investigate the role of attention and memory in error production to elucidate whether the types of errors made by children with developmental dyspraxia represent a delay in development or a pathology.

Summary and Suggestions for Clinical Application

Habilitation of the child with dyspraxia requires an understanding of the motor, sensory integrative, and cognitive and conceptual components of movement. The literature reviewed in this paper may help us to better understand the types of problems seen in children with developmental dyspraxia. Roy (1982), Roy and Square (1985), Ayres (1985), and Cerntak (1985) have clarified the distinction between the planning and execution phases of motor actions. Motor organization can be viewed as a delicate balance between open- and closed-loop modes of control and conceptual and data-driven styles of organization. The cognitive aspects of the task have been identified as important components of performance and are related to the nature of the task, the level of performance, and the environmental context. Kelso and Tuller (1981)
have further emphasized how a coalitional style of organization decreases the problem of too many unconstrained degrees of freedom (decisions) and produces a compatibility between the person and the environment. Premovement organization, or pretuning of the postural system, may be considered a component of preplanned voluntary responses, helping to ready the motor action system for upcoming actions. Selection of the most functionally appropriate information also helps ready the system for upcoming actions. Lastly, further examination of the normal processes of skill acquisition and motor action errors observed in normality and pathology may direct us toward the development of more effective evaluation and treatment for children with developmental dyspraxia.

Clinicians working with children with developmental dyspraxia may need to address rule learning; the appropriate use of context cues, problem solving, and task analysis; and the effective use of knowledge of performance as well as improved production of motor output. Gibson (1969) described three processes in perceptual learning: abstraction, filtering of irrelevant variables, and selective attention. These processes can be applied when assisting the child with difficulty in motor planning and motor learning. For example, to help the child learn rules and the appropriate use of context cues, one can point out rules and similarities and assist the child in the identification of critical dimensions. We may need to point out the relationships or contiguity between the child’s actions and the consequences, so that the child can more effectively use knowledge of results. Varying practice demands and conditions of practice with consequent feedback and guidance will enable the child to begin to develop schemata or generalizations.

Goal-directed activities help ready the child for upcoming movements and can also help develop effective use of knowledge of results. Sometimes the therapist does not make the goal of an activity clear to the child. For example, the therapist working to help improve the child’s dynamic balance may not clearly identify to the child that the goal of the activity is to walk across a mat (i.e., an unstable surface) without tripping. If the therapist does not make the child aware of the goal, the child will have more difficulty readying herself or himself. The child may need assistance in creating an image of what the action encompasses. In addition, successful completion of the action is important because it helps the child develop adequate goal expectations and because future performance can be compared with successful experience. The therapist can reduce the amount of assistance provided as the child’s performance improves.

Therapists need to thoroughly analyze the characteristics and complexity of the tasks selected as therapeutic activities. Sometimes therapists limit analysis to the type of muscle groups used (e.g., proximal versus distal musculature, gross versus fine motor activity). The tasks should also be analyzed in regard to the mode of control (e.g., reliance on ongoing feedback versus premovement organization). Additionally, the conceptual and sensory integration components of the task should be carefully considered, and the tasks should be evaluated functionally within the context of the environment. The use of a taxonomy of motor tasks may help the therapist assess motor planning or select movement experiences for children during therapy (e.g., Gentile’s [1972] Taxonomy of Motor Tasks).

In addition, the specific demands of the task need to be viewed in conjunction with the unique learning abilities and learning styles of each child. The nature of the child’s strengths and difficulties must be specifically analyzed. For example, in terms of motor skill acquisition, the dyspraxic child may remain in the early phase of motor skill acquisition with continuous cognitive regulation. In this feedback, or closed-loop, mode, the child is reacting to changes rather than anticipating upcoming events. Also, the child may be too aware of the environmental cues, some of which may be irrelevant. The therapist, therefore, may assist the child by identifying the most salient cues. Cognitive strategies may need to be modified as the child becomes more proficient.

Lastly, therapeutic programs for children should be simultaneously fun and challenging. Optimal arousal and motivation have been identified as critical to motor learning (Koomar, in press; Singer, 1978). To maximize the child’s interest and involvement, the therapist can have the child participate in the selection and organization of activities. The activities need to be playful and enjoyable and should allow the child to experience success.

In conclusion, motor planning problems of the child with developmental dyspraxia are complex and may occur for various reasons. Gibson (1988) described exploration as an active process with a perceptual, cognitive, and motor aspect and has emphasized the need for an integrated approach to the study of the individual’s interaction within the environment. To design appropriate remediation skills, careful attention must be given to the characteristics of the learner, the demands of the task, and the environmental context. The therapist needs to create a perfect match between the challenges of the activity and the abilities of the child.

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The American Occupational Therapy Association is pleased to announce that Lucy Jane Miller has been chosen to receive the Cordelia Myers Writer’s Award for the American Journal of Occupational Therapy’s 1989 volume year. Her paper, “Development of the Miller Screening for Preschoolers,” published in the September issue, was considered by the journal’s Editorial Board members to be the best piece of professional writing by a first-time contributor to the journal for that year.

The journal’s Editorial Board members and staff extend their congratulations to Lucy Jane Miller.