Research Report

Motor Learning of a Dynamic Balancing Task After Stroke: Implicit Implications for Stroke Rehabilitation

Background and Purpose. After a stroke, people often attempt to consciously control their motor actions, which, paradoxically, disrupts optimal performance. A learning strategy that minimizes the accrual of explicit knowledge may circumvent attempts to consciously control motor actions, thereby resulting in better performance. The purpose of this study was to examine the implicit learning of a dynamic balancing task after stroke by use of 1 of 2 motor learning strategies: learning without errors and discovery learning. Participants and Methods. Ten adults with stroke and 12 older adults practiced a dynamic balancing task on a stabilometer under single-task (balance only) and concurrent-task conditions. Root-mean-square error (in degrees) from horizontal was used to measure balance performance. Results. The balance performance of the discovery (explicit) learners after stroke was impaired by the imposition of a concurrent cognitive task load. In contrast, the performance of the errorless (implicit) learners (stroke and control groups) and the discovery learning control group was not impaired. Discussion and Conclusion. The provision of explicit information during rehabilitation may be detrimental to the learning/relearning and execution of motor skills in some people with stroke. The application of implicit motor learning techniques in the rehabilitation setting may be beneficial. [Orrell AJ, Eves FF, Masters RSW. Motor learning of a dynamic balancing task after stroke: implicit implications for stroke rehabilitation. *Phys Ther.* 2006;86:369–380.]

Key Words: *Motor learning, Rehabilitation, Stroke.*

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Balance control is a fundamental motor behavior in stance and gait that allows an individual to maintain and adopt various postures, react to external perturbances, and use automatic postural responses that precede voluntary movements.[1,2] After stroke, many people find it more difficult to perform some or all of these tasks. Thus, the learning/relearning of balance control is a primary goal of stroke rehabilitation.

Balance control requires the integration of visual, somatosensory, and vestibular inputs and their adaptations to changes in the environment and in the task being performed.[3] Some degree of attention is required to maintain balance,[1,4–6] with greater attentional demands after stroke.[7] Furthermore, higher integrative levels have a role in balance control, because the introduction of a concurrent cognitive task, such as talking, can impair balance after stroke.[8,9] Indeed, a loss of fluency and automaticity of balance control after stroke has been attributed to a trade-off among available cognitive resources.

As a corollary to stroke, cognitive deficits can occur in the domains of language, orientation, attention, and memory.[10–12] Such deficits will affect the ability of people to learn/relearn motor skills. Current rehabilitation therapies, which are based on traditional motor learning theories, typically involve the concurrent performance of motor and cognitive tasks. Thus, people receive many complex and explicit instructions on how to perform tasks and are encouraged to evaluate performance outcomes. The provision of many explicit instructions by the therapist may be confusing for people because cognitive deficits affecting memory and attention are associated with a reduction in the speed of information processing. Thus, many people with stroke find it very difficult to perform concurrent tasks, such as walking and listening, during rehabilitation. Crucially, the learning or relearning of motor skills with a concurrent cognitive task may be diminished by the presence of cognitive deficits after stroke, calling into question the effectiveness of current rehabilitation strategies. A learning or relearning strategy that minimizes concurrent cognitive tasks would be particularly advantageous for stroke rehabilitation.

Implicit learning refers to the learning of information without the ability to verbally describe the knowledge of what is learned. Implicit learning is characterized as being a relatively passive process in that people are exposed to information and can acquire knowledge of that information simply through exposure, such as language learning and learning to ride a bicycle.[13,14] In contrast, *explicit learning* is related to the ability to describe verbally something that is being learned, such as tying a shoelace, and is characterized as an active process in which people seek out the structure of any information that is presented to them, such as solving a geometric problem and hypothesis testing.[13,*]

Conventional wisdom advocates that motor skill control progresses from explicit or conscious control in the early stages of learning to a more implicit or automatic control when well learned.[15,16] In the early stages, rules to avoid performance errors can be recalled consciously or explicitly as the learner attempts to avoid errors during succeeding performances. As learning continues, these explicit rules are lost or "forgotten" as the processing of task-relevant information becomes unconscious. The skill then is referred to as being automated or implicit.[15,16] A limitation of explicit processing, however, is its dependence on the cognitive resources of working

* *Procedural knowledge* refers to "knowing how" and underlies the performance of actions. *Declarative knowledge* refers to "knowing what" and is knowledge of facts and relationships. For the purposes of this article, the distinction between declarative knowledge and procedural knowledge can be equated approximately with the distinction between explicit knowledge and implicit knowledge, as implicit knowledge, like procedural knowledge, is generally inaccessible, whereas declarative knowledge is generally accessible and thus is explicit. Therefore, implicit learning encompasses procedural knowledge, but the 2 terms are not interchangeable.

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memory.† More recent approaches to motor skill acquisition emphasize that implicit learning occurs independently of the influence of explicit knowledge.[17] *Implicit motor learning* refers to the acquisition of a motor skill without the concurrent acquisition of explicit or verbal knowledge about the performance of that skill.[18] Implicit processes are considered to function independently of working memory.[19] Thus, skill acquisition always involves implicit learning and questions the assumptions of traditional motor learning models, in which skill acquisition proceeds from an explicit state to an automated state.[20,21] Recent research on the implicit acquisition of motor skills supports this premise, as the implicit learning of complex motor skills, such as golf putting and the topspin forehand in table tennis, has been demonstrated in people who are nondisabled.[18,22–25]

Several strategies have been developed to promote implicit motor learning in people who are nondisabled: learning with a concurrent task of random-letter generation to block working memory[18]; learning by analogy,[23,26] in which the biomechanical rules of a task are disguised in the form of an image (eg, the topspin forehand in table tennis has been successfully taught with the analogy of bringing the bat up the hypotenuse of a right-angled triangle[23]); and learning without errors.[25] These strategies are hypothesized to promote an implicit mode of motor learning by impeding or circumventing explicit processing and so disrupting the accumulation of explicit knowledge relating to the motor skill to be learned. Particularly promising for learning/relearning after stroke is the strategy of learning without errors because it requires no additional cognitive load.[25] By reducing the number of errors made by the learner during skill acquisition, the opportunity for the explicit testing of hypotheses and error correction is reduced. Inhibition of the formation of explicit knowledge of the task is hypothesized to promote an implicit mode of learning.[25] This hypothesis has been tested by reducing the number of errors made by the learner when learning a golf putting skill.[25] Errorless learners produced a higher level of performance during retention than explicit learners, and their performance was robust when a concurrent cognitive task was added. The authors concluded that the skills acquired in an error-free environment lessened the demand for explicit attentional resources.[25] In addition, the authors concluded that learning without errors conferred an implicit and robust mode of learning.[25]

Implicit motor learning of a dynamic balancing task recently was investigated in a sample of young adults who were nondisabled.[27] Participants were required to keep a stabilometer platform horizontal for 60 seconds in each trial. In that study, 3 different learning conditions were tested. Two groups learned with strategies to promote implicit learning, that is, either analogy learning or errorless learning, whereas the third group (explicit learning) was required to actively discover the rules of the task. The results showed that learning of the balancing task was implicit in character for the analogy learners and for the errorless learners (ie, the learners accumulated a minimal number of explicit rules of the task), and the learning was durable over time and robust under secondary task loading. Interestingly, balance performance improved when the verbal component of working memory was occupied with a nonbalancing task (either a number recall task or a tone counting task). The authors reasoned that implicit processes were the main contributors to the learning of and performance of the balancing task and that the use of explicit, verbal information while performing the balancing task actually impeded optimal performance. This finding has implications for rehabilitation. After a stroke, people often attempt to consciously control their motor actions,[28,29] whereas people who are nondisabled seldom use conscious control for routine movements.[30] A learning strategy that impairs the accumulation of explicit knowledge may circumvent attempts to consciously control motor action, thereby resulting in better performance.[18]

The application of implicit motor learning strategies may be beneficial in stroke rehabilitation. Implicit learning confers robustness of performance with a concurrent task and is durable over time.[13] Furthermore, recent evidence from the implicit learning literature suggests that implicit learning processes are retained in some people with stroke when tested with a serial reaction time task.[31–33] To date, however, no studies have investigated the application of implicit motor learning techniques after stroke by use of a "real-life" task. Thus, the purpose of this study was to investigate the implicit motor learning of a dynamic balancing task after stroke by use of an errorless learning paradigm. People after stroke and a control group learned a dynamic balancing task with 1 of 2 different strategies. Thus, an errorless learning strategy (implicit) was compared with a conventional discovery learning strategy (explicit). We hypothesized that learning without errors would promote learning that was implicit in character. Three criteria of implicit learning were used to test this hypothesis: the

† Working memory is a 3-part active system that stores and manipulates information while people perform cognitive tasks. Working memory consists of a central executive, the phonological loop, and the visuospatial sketch pad. The central executive is a multimodal, attentional system that supervises and coordinates a number of subsidiary "slave" systems. The phonological loop is involved in speech-based tasks, that is, understanding the speech that people hear and producing speech, both aloud and subvocally. In contrast, the visuospatial sketch pad is involved in the processing of nonverbal aspects of visual images and movement defined by allocentric coordinates. Both the phonological loop and the visuospatial sketch pad are limited-capacity, modality-specific storage systems of working memory.

Table 1.
Demographic and Clinical Information for the Stroke and Control Groups

Group	Site of Infarct (No. of Participants)	Sex	Age (y)		Educaton (y)		Clinical Symptoms (No. of Participants)	Mini-Mental State Examination Score		Berg Balance Scale Score	
			$\overline{X}$	SD	$\overline{X}$	SD		$\overline{X}$	SD	$\overline{X}$	SD
Stroke											
Errorless learners	Right hemisphere (2), left hemisphere (2), cerebellum (1)	4 men, 1 woman	49.20	15.71	14.60	2.58	Hemiparesis (4), hemiparesis + dysphasia (1)	26.80	0.84	38.40	5.82
Discovery learners	Right hemisphere (3), left hemisphere (1), bilateral hemispheres (1)	5 men	54.60	12.16	11.80	1.83	Hemiparesis (5)	25.80	1.30	38.00	8.99
Control											
Errorless learners		3 men, 3 women	67.17	8.69	13.30	2.05		29.17	0.69	52.30	1.37
Discovery learners		3 men, 3 women	63.17	5.27	13.70	1.80		29.33	0.75	53.50	0.76

accumulation of few explicit rules, the durability of learning over time, and the robustness of performance under a concurrent cognitive load.[13,23,25] We predicted that the errorless learners would acquire less explicit knowledge of the kinematic mechanisms of the balancing skill than the discovery learners. In addition, we predicted that a concurrent cognitive task would impair performance in the discovery learners but not in the errorless learners, on the grounds that skills learned without explicit learning should be unaffected by the presence of a concurrent task. Finally, we predicted that the durability of learning would be evident in a delayed retention test for the errorless learners but not for the discovery learners.

Method

Participants

Twelve participants with stroke resulting in hemiparesis and aged 28 to 69 years ($\overline{X}$=52.17 years, SD=11.27) and a control group of 12 adults who were neurologically intact and aged 52 to 75 years ($\overline{X}$=65.25 years, SD=7.48) volunteered to participate in the study (Tab. 1). Participants were recruited from several stroke groups in the West Midlands, United Kingdom, and from advertisements placed in a university staff magazine and a local newspaper. Participants with stroke fulfilled the following inclusion criteria: diagnosis of first stroke at least 12 months before the study to reduce the potential of spontaneous recovery confounding the data, discharge from all rehabilitation services, ability to understand instructions and to give informed consent, and no obvious cognitive or perceptual problems on the Mini-Mental State Examination.[34] A score of less than 24 on the Mini-Mental State Examination[34] is indicative of dementia. Computed topography scans confirmed that one participant had brain damage to the right cerebellum and that another participant had experienced bilateral stroke. The remaining participants had stroke syndromes consistent with brain lesions involving the anterior circulation system, as classified by Bamford et al.[35] The Bamford classification of stroke is widely applicable for community-based studies or when a narrow therapeutic time window exists because it is simple and relatively easy to use (Appendix). In summary, the participants in the stroke group had motor or sensory deficits, or both, in at least 2 of 3 body areas (face, arm, and leg), and one participant also had dysphasia. All participants gave informed consent and were naive with regard to the task.

Experimental Design

For this study, we used a mixed factorial design for repeated measures. The study was divided into 3 distinct phases: an acquisition phase followed by a separate test

Table 2.
Characteristics of Blocks in the Acquisition and Test Phases

Blocks	Day	Condition	Description
1–24	1	Acquisition	Balancing task only
25+26	1	Test	Retention test—primary balancing task only
27+28	1	Test	Primary balancing task plus number recall task
29+30	1	Test	Retention test—primary balancing task only
31+32	1	Test	Primary balancing task plus kettle lift task
33+34	2	Delayed retention	Delayed retention test—primary balancing task only

phase and a delayed retention test performed 1 week after the acquisition and test phases (Tab. 2).

Instrumentation and Task

Before commencing the balancing task, all participants were instructed to keep the stabilometer platform horizontal throughout each 60-second trial. Participants in the discovery learning groups also were instructed to discover rules of how to perform the balancing task. In the acquisition phase, all participants performed twenty-four 60-second trials of the balancing task. Control group participants had a 2-minute rest interval between trials, whereas participants with stroke had longer rest intervals if needed. During the rest intervals, all participants attempted a jigsaw puzzle to inhibit the formation of explicit knowledge about the balancing task gained from explicitly processing task-relevant information. The acquisition phase was followed by a 15-minute rest interval, during which participants continued with the jigsaw puzzle.

The test phase was begun after the 15-minute rest interval. Participants performed 2 retention tests and 2 separate transfer tests. Each transfer test followed a retention test. During the retention tests, participants performed two 60-second trials of the primary balancing task. For the transfer tasks, participants performed two 60-second trials of the balancing task with a concurrent secondary task presented during the final 30 seconds of each trial. The first transfer task was a verbal cognitive task that required participants to recall random 6-digit sequences presented at a rate of 1 per second. This task was chosen because it is similar to being told a telephone number by another person. The number recall task was designed to suppress the use of any verbal knowledge of the balancing task by blocking the phonological loop of working memory.[36]

The second transfer task was primarily a nonverbal motor task that required participants to shift their center of gravity in order to reach out and pick up and hold a 1-kg kettle with 1 hand. This task was chosen because it imitates the everyday task of lifting a full kettle of water. To maintain balance, participants needed to make postural adjustments. Participants with stroke used the hand ipsilateral to the side of the stroke to lift the kettle. Control group participants were matched for handedness with stroke group participants for this task. The participant with bilateral stroke performed this task with the dominant hand. On completion of the test phase, the participants' explicit knowledge of the balancing task was assessed by use of verbal protocols. Participants were asked to record any "rules, methods, or techniques" that they had thought about or used and that had enhanced or impaired their balance performance. These verbal protocols were scored by assessing and summing the number of explicit rules associated with the kinematic aspects of the balancing task. A delayed retention test was performed 1 week after the acquisition and test phases. This test required participants to perform two 60-second trials of the primary balancing task.

All participants performed the balancing task on a stabilometer and were required to wear a full-body safety harness with a rear "D" ring fall arrest attachment point throughout the experiment to remove the fear of falling from the stabilometer platform (Fig. 1). Fear of falling is common among older people,[37] and people with stroke have a high risk of falling on hospital discharge and during rehabilitation.[29,38,39] The stabilometer platform (100×67 cm) was freely mounted on a horizontal axis in the participants' frontal plane. A maximum range of motion of 30 degrees of deviation from horizontal was available. Performance data were collected with a linear potentiometer mounted on the horizontal axis and sampled at 500 Hz by a PC with a C.E.D. 1401 *plus* data acquisition board.[‡] The C.E.D. 1401 *plus* acquisition board records waveform data, and the on-board processor with high-speed memory allows for real-time processing. Data capture and analysis were performed with Spike 2 version 3 software.[‡]

Procedure

Participants from the stroke and control groups were randomly assigned to 1 of 4 groups: (1) errorless learning stroke group, (2) errorless learning control group, (3) discovery learning stroke group, and (4) discovery learning control group. At the beginning of the acquisition phase, all participants were instructed to keep the stabilometer platform horizontal throughout each 60-second trial. The discovery learning groups also were instructed to discover rules of how to perform the balancing task. In the errorless learning groups, a brak-

‡ Cambridge Electronic Design Ltd, Science Park, Milton Rd, Cambridge, CB4 0FE United Kingdom.

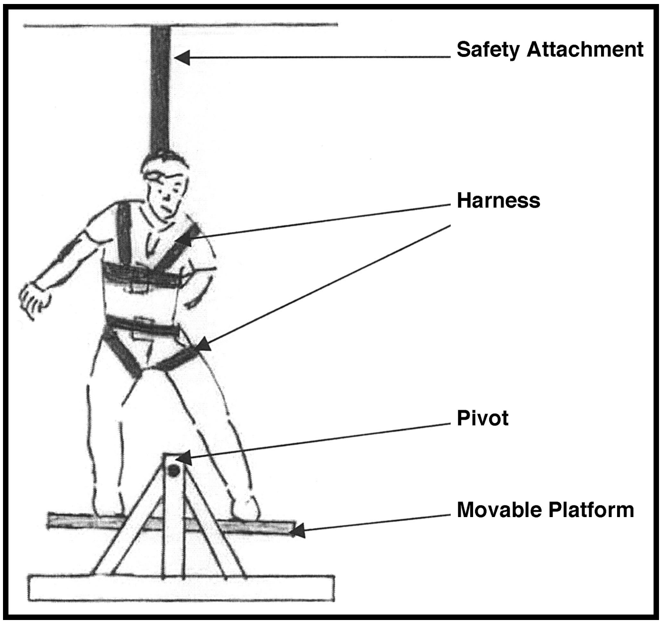

Figure 1.
Schematic diagram of a participant on the stabilometer.

ing resistance of 2.5 kg was applied to the stabilometer fulcrum to fully restrict movement of the stabilometer platform. This resistance was progressively decreased by 0.5 kg after multiples of 4 trials such that no resistance occurred in the final 4 trials of acquisition and during the test and retention phases; that is, the stabilometer platform swung freely. To minimize the possibility of a ceiling effect on performance, that is, all participants performing at nearly perfect levels, the movement of the stabilometer platform was fully restricted for the first 4 acquisition trials only. Although the errorless condition does allow some errors to occur, it is conventional to call the substantial reduction in errors during learning "errorless" to contrast it with conditions in which no attempt is made to minimize errors.[25] During acquisition, the stabilometer platform was placed in the horizontal position for the errorless learners. For the start of all other trials, the stabilometer platform was resting on the left side. Data collection began when the platform crossed horizontal.

Measures

The Berg Balance Scale[40] was administered before testing to assess the participants' balance ability. No pretest measures of performance on the balancing task were recorded because exposure to the task before acquisition might have encouraged participants in the errorless learning conditions to adopt a hypothesis-testing strategy, thus promoting an explicit rather than an implicit mode of learning. Root-mean-square error (RMSE) (in degrees) about the midpoint in the vertical axis of the stabilometer was used as a measure of balance performance during all experimental phases.

Data Analysis

During the course of the study, 2 participants with stroke withdrew. Thus, all statistical analyses were conducted on the data obtained from participants who completed the study. To determine whether the stroke and control groups were matched for balance ability, baseline balance ability was assessed by use of a 2×2 (group [stroke, control]×condition [errorless, discovery]) analysis of variance (ANOVA) with pretest score on the Berg Balance Scale[40] as the dependent measure.

Acquisition performance was assessed over averaged pairs of trial blocks by use of a 2×2×11 (group [stroke, control]×condition [errorless, discovery]×block [1, 2, 3. . .11]) multivariate analysis of variance (MANOVA) with repeated measures for block and with RMSE as the dependent variable. All data were normally distributed with a skewness of $<$1.0, and the Fmax test for heterogeneity of variance between groups or conditions was never significant (all P values were $>$.20). All analyses included, when appropriate, the epsilon correction for the degrees of freedom to counteract any violation of the assumption of equality of covariance across repeated measures. This correction is referred to throughout this article as repeated-measures correction. *Post hoc* tests were performed to identify the locus of interactions. Separate analyses of the 2 learning conditions were carried out by use of a 2×11 (group [stroke, control]×block [1, 2, 3. . .11]) univariate ANOVA with repeated-measures correction for block and with RMSE as the dependent variable.

Retention and delayed retention test data were used to reflect motor learning of the balancing task and the durability of this learning over a period of 1 week. Learning was assessed over averaged pairs of trial blocks by use of a 2×2×3 (group [stroke, control]×condition [errorless, discovery]×block [A12, R1, R3]) MANOVA with repeated-measures correction for block and with RMSE as the dependent measure.

Averaged pairs of trial blocks of test-phase data were used to examine balance performance under secondary task loading by use of a 2×2×2×2 (group [stroke, control]×condition [errorless, discovery]×task [number recall, kettle lift]×pre-30 seconds versus post-30 seconds [balance alone during the first 30 seconds versus balance with secondary task during the last 30 seconds]) MANOVA with repeated-measures correction for task and pre-30 seconds versus post-30 seconds and with RMSE as the dependent measure. Separate analyses were run for each task by use of a 2×2×2 (group [stroke, control]×condition [errorless, discovery]×pre-30 seconds versus post-30 seconds [balance alone during the first 30 seconds, balance with secondary task during the last 30 seconds]) MANOVA with repeated-measures cor-

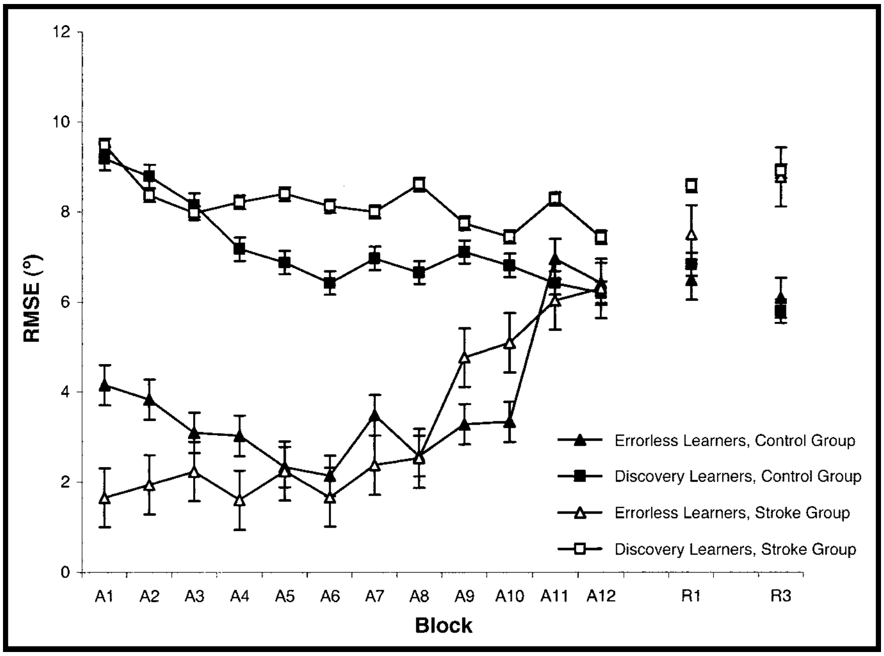

Figure 2.
Performance (mean and standard error) of the stroke and control groups in the 2 conditions over averaged pairs of trials during acquisition, retention, and delayed retention. RMSE=root-mean-square error, A=acquisition trial number, R1=first retention test, R3=delayed retention test.

rection for pre-30 seconds versus post-30 seconds and with RMSE as the dependent variable. *Post hoc* tests were performed to identify the locus of interactions by use of separate 1-way ANOVA and paired *t* tests. Verbal protocols were assessed by use of a 2×2 (group [stroke, control]×condition [errorless, discovery]) ANOVA. *Post hoc* analysis with the Student-Newman-Keuls test, $P<.05$ test was performed to identify the locus of interactions. The alpha level for all analyses was set at $P<.05$.

Results

Balance Ability

Although balance ability within the different groups (stroke, control) was comparable on the Berg Balance Scale[40] ($F=0.007$; $df=1,18$; $P=.935$), as might be expected, the balance abilities of the 2 stroke groups were significantly poorer than those of the 2 control groups ($F=1{,}456.09$; $df=1,18$; $P<.001$).

Acquisition Phase

Inspection of Figure 2 indicates that RMSE decreased across blocks for the discovery learning groups during acquisition but increased across blocks for the errorless learning groups. When the 2 learning conditions were considered separately, no group×block interaction was revealed for either the errorless learning condition ($F=1.67$; $df=10,90$; $P=.20$) or the discovery learning condition ($F=1.88$; $df=10,90$; $P=.16$).

Retention and Delayed Retention

To demonstrate learning of the balancing task, rather than an improvement in performance, no changes in RMSE should have occurred for any of the 4 groups over the time between the end of acquisition (A12) and the first retention block (R1) in the test phase. In addition, because durability over time is a characteristic of implicit learning, no changes in RMSE should have been observed over a period of 1 week (R3). There were no significant changes in balance performance scores across the 3 blocks ($F=2.64$; $df=2,17$; $P=.10$), suggesting that learning was retained over time for all groups. Inspection of Figure 2 confirms the maintenance of learning in the delayed retention test after 1 week (R3). Importantly, the lack of a group×condition×block interaction ($F=0.39$; $df=2,17$; $P=.70$) suggests that all groups had learned the balancing task equivalently and maintained that learning over time.

Test Phase

We predicted that balance performance would be impaired by a concurrent task in the discovery learning groups but not in the errorless learning groups under secondary task loading. These findings would be reflected by an increase in RMSE for the discovery learning groups under secondary task loading. Figure 3 depicts the performance of the different groups in the test phase when either number recall or kettle lift was added to the balancing task. Initial analysis of the secondary tasks (number recall and kettle lift) revealed a significant group×condition×task×pre-30-second versus post-30-second interaction ($F=5.71$; $df=1,18$; $P=.028$). There was a difference in performance under the conditions of balance only and balance under secondary task loading for groups, learning conditions, and secondary tasks. Therefore, separate analyses of the number recall and kettle lift secondary tasks were performed.

Number Recall

Inspection of Figure 3 shows the effects of the addition of the concurrent number recall task. Balance performance improved for the errorless learning stroke group ($F=13.52$; $df=1,4$; $P=.021$) under secondary cognitive loading and declined for the discovery learning stroke group ($F=9.75$; $df=1,4$; $P=.035$). No impairment in performance was revealed for the errorless learning

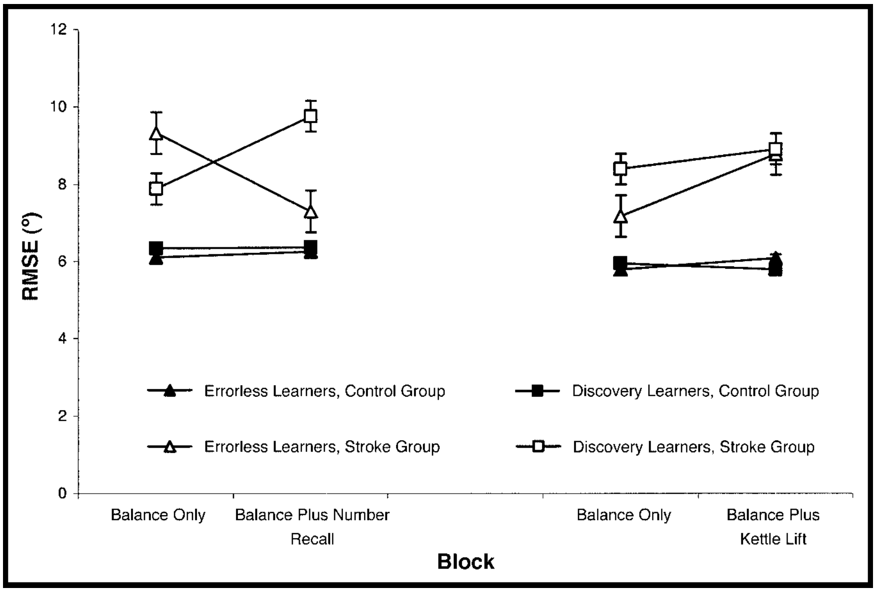

Figure 3.
Performance (mean and standard error) of the stroke and control groups in the 2 conditions over averaged pairs of trial blocks during the test phases. RMSE=root-mean-square error.

control group (F=0.15; *df*=1,5; *P*=.72) or the discovery learning control group (F=0.01; *df*=1,5; *P*=.94).

Kettle Lift

There were no differences among the groups between the first 30-second and the second 30-second period of the trial blocks (F=0.25; *df*=1,18; *P*=.63). No decline in performance was revealed for the errorless learning stroke group (t_4=1.44; *P*=.23). This result indicates that balance performance was robust in all groups when reaching for, lifting, and holding the kettle.

Verbal Protocols

Verbal protocol scores were established by summing the number of explicit rules relating to kinematic aspects of the task. The ANOVA revealed a main effect of condition (F=9.58; *df*=1,18; *P*=.007). *Post hoc* analysis (Student-Newman-Keuls test, *P*<.05) showed that the discovery learning stroke group ($\overline{X}$=3.40, SD=1.34) accumulated more explicit rules than the discovery learning control group ($\overline{X}$=2.67, SD=1.03), the errorless learning control group ($\overline{X}$=1.83, SD=0.75), and the errorless learning stroke group ($\overline{X}$=1.40, SD=1.14).

Discussion

The findings of this investigation support the hypothesis that learning without errors promotes nonverbal learning and that this learning is implicit in character. This conclusion is evidenced by the durability of learning over time, the robustness of performance with concurrent cognitive task loading, and the accrual of minimal explicit knowledge of the mechanics of the task in the errorless learning groups. These results support previous findings[25,27] and suggest that learning without errors promotes an implicit mode of motor learning by inhibiting the acquisition of explicit knowledge.

Evidence of delayed retention is considered to be an important criterion for demonstrating learning, as learning is epitomized as a permanent change in behavior.[41] Although the discovery learning groups demonstrated a reduction in RMSE during acquisition, this result may have been an expression of improved performance of the task rather than learning.[42] To demonstrate learning of the balancing task, rather than an improvement in performance, no changes in RMSE should have occurred for any of the 4 groups over the time between the end of acquisition (A12) and the first retention block (R1) in the test phase. In addition, because durability over time is a characteristic of implicit learning, no changes in RMSE should have been observed over a period of 1 week. The absence of a group×condition×block interaction suggests that all groups had learned the balancing task, that there were no differences in learning of the task among the groups, and that this learning was retained over time.

The accumulation of minimal explicit knowledge of the task to be learned is a characteristic of implicit motor learning. It was predicted that participants in the errorless learning groups would accrue significantly fewer explicit rules of the task than participants in the discovery learning groups but that no differences would be found between the groups in the errorless learning condition. It is possible, however, that the performance of the errorless learners became more explicit as the potential to make errors and thus to use hypothesis-testing processes increased during acquisition with the decrease in resistance on the stabilometer platform. Verbal protocols do not support this contention, as the number of rules reported after learning by the errorless learners (stroke and control groups) was smaller than the number of rules reported by the discovery learners (stroke and control groups). This finding was expected because the discovery learners (stroke and control groups) were required to actively discover rules relating to the task, and participants with stroke are more likely to consciously try to control the execution of their motor actions.[28,29] Indeed, Maxwell et al[25] suggested that initial learning under implicit conditions confers robustness to performance under concurrent task conditions even when explicit rules are subsequently accumulated.

During the acquisition, retention, and delayed retention phases, the performance of the stroke groups was consistently poorer than that of the respective control groups. Pretest scores on the Berg Balance Scale[40] clearly demonstrated a disparity in balance ability between the stroke and the control groups but no disparity within the stroke groups. Although both of the stroke groups displayed poorer balance performance throughout, the disparity in performance between the errorless learners and the discovery learners with stroke on the concurrent number recall task is of interest. It was predicted that balance performance would be impaired by a concurrent task in the discovery learning groups but not in the errorless learning groups under secondary task loading. This effect would be reflected by an increase in RMSE for the discovery learning groups in the second 30-second period of the transfer tasks. An improvement in balance performance for the errorless learning stroke group when the balancing task was combined with the number recall task contrasted with the impaired performance for the discovery learning stroke group. Thus, a verbal task impaired performance in the discovery learners but improved performance in those learning with the errorless protocol. The impaired performance of discovery learners would be consistent with these participants attempting to control their motor actions consciously after stroke[28,29] but having these efforts disrupted by a concurrent verbal task.

The improved performance of the errorless learners with stroke when the verbal system was engaged in the number recall task suggests that the balancing task was performed better nonverbally. Previous studies[43–45] have demonstrated improvements in nonverbal tasks when the verbal system is otherwise engaged. In a series of studies, Brandimonte and coworkers[43–45] demonstrated that a concurrent verbal task improved the performance of image manipulation tasks. They argued that verbal recoding of a nonverbal stimulus impaired or degraded long-term memory for that stimulus. Brandimonte et al[43] also concluded that with a concurrent verbal task, encoding of the stimuli visually rather than verbally produced optimal performance. Similarly, Schooler and Engstler-Schooler[46] demonstrated that verbalization of nonverbal tasks can interfere with successful performance. Thus, the improvement in balance performance for the errorless learning group with stroke during the number recall task would suggest that optimal performance is inhibited by the application of verbal information regarding this task during the balancing task.

Although the errorless learning groups demonstrated characteristics of implicit motor learning, the results revealed that the balance performance of the discovery learning control group was not impaired under secondary task loading. This finding is contrary to our prediction that the balance performance of the discovery learning control group would be impaired by a concurrent cognitive task because dual verbal tasks are hypothesized to interfere with the application of explicit knowledge.[47] There are several possible theoretical reasons for this finding. First, the number recall task may have been too simple to cause interference, as complex tasks that require more processing are associated with greater interference in postural control than simpler tasks.[4,6] This explanation, however, seems improbable, as the presented 6-digit number recall task is difficult to perform successfully. As recommended by Baddeley,[36] the random 6-digit sequences were presented at a rate of one per second in order to suppress the use of verbal knowledge by blocking the phonological loop of working memory. Second, assuming that the discovery learning control group participants were running the balancing task explicitly, the amount of available explicit knowledge may not have presented a large enough processing load to saturate processing capacity during performance of the concurrent task. Alternatively, the similarity of the performance curves for the discovery learning control group and the errorless learning groups during the test phase suggests that the discovery learning control group participants did not use their available explicit knowledge to perform the balancing task. As previously noted, the presence of explicit knowledge does not necessarily mean that the knowledge must be used.[17]

The preservation of nonverbal learning with a concurrent cognitive task (number recall) is consistent with implicit processes occurring in parallel with processes that are more dependent on the availability of explicit knowledge.[14] Gentile[48] suggested that skill acquisition is mediated by a rapid explicit process that conveys the performer-environment relationship and a slower implicit process that establishes the functional dynamics of the movement. These processes therefore may be used in parallel during performance of the skill. Thus, a concurrent verbal task may alter the relative contributions of the implicit and explicit processes to the performance of any nonverbal task. In our study, participants were required to perform the balancing task for 60 seconds. In the balance-only condition, participants may have been using explicit knowledge from the environment and from action outcomes to explicitly run the task. When the verbal system was engaged with the number recall task, the absence of impairment in balance performance for the errorless learning groups and the discovery learning control group suggests that implicit processes were the main contributors to task performance, whereas in the balance-only condition, explicit processes also may have contributed to task performance.

In contrast to the number recall task, the shifting of the center of gravity in the kettle lift task had no significant effect on balance performance for all groups. Although an increase in RMSE was observed for the stroke groups when lifting the kettle, this finding may have been a reflection of temporal and individual differences in regaining balance on the stabilometer. In order to regain balance after reaching and lifting the kettle, participants with stroke would have had to shift their weight onto their affected limb. This process would take longer to achieve for participants with reduced weight-shifting abilities than for participants with intact weight-shifting abilities.[49]

The findings of this study demonstrated that participants with stroke benefited from using an errorless (implicit) learning strategy to learn a dynamic balancing task. Learning for the errorless learning groups was durable over time and robust in the presence of concurrent cognitive task loading. In comparison, learning of a dynamic balancing task by participants with stroke and using an explicit learning strategy resulted in durable learning over time, as evidenced by the results of the delayed retention test, but in less robust learning and subsequent motor performance in the presence of concurrent cognitive task loading.

However, care must be taken in directly extending the results of this laboratory-based study to clinical practice. First, the small sample size suggests that caution is appropriate at this stage for nonsignificant comparisons between groups. Power calculations for differences between groups or conditions suggest that there was only 36% power to detect a large effect. In contrast, the relatively high correlation between repeated measures (typical Pearson *r* value of $>.80$) means that there was more than 80% power to detect differences between repeated time points.[50] Consequently, the within-subject effects can be viewed with greater confidence. Second, the laboratory task of balancing on a stabilometer, while similar, is not directly comparable to real-life balance; it is more like standing astride a seesaw. Thus, lifting a kettle may produce an imbalance in an individual but would not inevitably destabilize the surface on which that individual is standing. Therefore, generalization of the results to the general population of people with stroke should be made with caution.

Conclusions

It appears that errorless learning strategies promote nonverbal learning that is implicit in character. The results of this study suggest that the application of errorless learning strategies may be of benefit in the rehabilitation of people with stroke. First, it appears that verbal knowledge or attempts to control tasks with the verbal component of working memory may be problematic. Verbalization of a movement's parameters has been shown to exaggerate technical flaws in athletes attempting to achieve maximal performance, such as "choking" in tennis, whereby automatic execution processing becomes inhibited, resulting in subpar performance.[18,51] Masters et al[52] referred to this act of turning one's attention in toward the mechanics of an action as "reinvestment." Masters[18] argued that by acquiring a motor skill implicitly, the learner will be unable to reinvest, as the learner will have no verbal knowledge of the mechanics of the movement. Thus, conscious interference with the motor commands during performance will be averted.

Concerning errorless techniques themselves, one effective strategy in non–movement-impaired participants is to gradually progress from a very easy condition to more difficult versions of the same task.[25] The rationale behind this approach is that a minimization of errors should reduce the need to test hypotheses and thus the accrual of explicit verbal knowledge about the movement kinematics. This approach could be applied to the learning/relearning of real-life sit-to-stand actions[53] and to fine coordination skills, such as turning a key in a lock or picking up a cup.[54] For example, for a sit-to-stand action, the learner would have to reach for an object on a table. Initially, the object would be very close at hand so that the learner could reach it. Gradually over trials, the distance between the object and the learner would be increased. Thus, the learner would have to stand to reach the object. With a progressive increase in the distance between trials, error would be kept to a minimum, a corollary being an increase in leg muscle strength. Dean and Shepherd[53] previously used this technique but did not refer to it as errorless learning, because they were evaluating the effectiveness of a training program aimed at increasing distance reached and the contributions of the affected lower leg to support and balance.

Errorless learning strategies have been successfully applied in the rehabilitation of people with memory impairments.[55] A further benefit of errorless learning may originate from the effects of error minimization on the performance of tasks that require conscious recollection of a previous episode,[56] that is, residual explicit memory.[57] People with stroke have a predisposition to rely on explicit knowledge of a movement, thereby disrupting optimal performance. Through minimization of the amount of available explicit knowledge during rehabilitation, subsequent motor performance may be enhanced. From an applied perspective, the results of our study suggest that implementation of errorless learning strategies may be beneficial in stroke rehabilitation. Additional studies are needed, however, to investigate the validity of implementing this paradigm in the rehabilitation context.

References

1 Marsh AP, Geel SE. The effect of age on attentional demands of postural control. *Gait & Posture.* 2000;12:105–113.

2 Walker C, Brouwer BJ, Culham EG. Use of visual feedback in retraining balance following acute stroke. *Phys Ther.* 2000;80:386–395.

3 Shumway-Cook A, Woollacott M. Attentional demands and postural control: the effects of sensory context. *J Gerontol A Biol Sci Med Sci.* 2000;55:M10–M16.

4 Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. *Exp Brain Res.* 1993;97:139–144.

5 Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M. The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *J Gerontol Biol Sci Med Sci.* 1997;52: M232–M240.

6 Teasdale N, Bard C, LaRue J, Fleury M. On the cognitive penetrability of posture control. *Exp Aging Res.* 1993;19:1–13.

7 Brown LA, Sleik RJ, Winder TR. Attentional demands for static postural control after stroke. *Arch Phys Med Rehabil.* 2002;83:1732–1735.

8 Bowen A, Wenman R, Mickleborough J, et al. Dual-task effects of talking while walking on velocity and balance following a stroke. *Age Ageing.* 2001;30:319–323.

9 Haggard P, Cockburn J, Cock J, et al. Interference between gait and cognitive tasks in a rehabilitating neurological population. *J Neurol Neurosurg Psychiatry.* 2000;69:479–486.

10 Hochstenbach J, Mulder T, VanLimbeek J, et al. Cognitive decline following stroke: a comprehensive study of cognitive decline following stroke. *J Clin Exp Neuropsychol.* 1998;20:503–517.

11 Hochstenbach J, van Spaendonck K, Cools A, et al. Cognitive deficits following stroke in the basal ganglia. *Clin Rehabil.* 1998;12: 514–520.

12 Tatemichi TK, Desmond DW, Stern Y, et al. Cognitive impairment after stroke; frequency, patterns and relationship to functional abilities. *J Neurol Neurosurg Psychiatry.* 1994;57:202–207.

13 Berry DC, Dienes Z. *Implicit Learning: Theoretical and Empirical Issues.* Hove, United Kingdom: Lawrence Erlbaum Associates Ltd; 1993.

14 Cleermans A, Destrebecqz A, Boyer M. Implicit learning: news from the front. *Trends Cogn Sci.* 1998;2:406–416.

15 Anderson, JR. *The Architecture of Cognition.* Cambridge, Mass: Harvard University Press; 1983.

16 Fitts PM. Posner MI. *Human Performance.* Belmont, Calif: Brooks/ Cole; 1967.

17 Jimenez L, Mendez C. Implicit sequence learning with competing explicit cues. *Q J Exp Psychol A.* 2001;54:345–369.

18 Masters RSW. Knowledge, knerves and know-how: the role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *Br J Psychol.* 1992;83:343–358.

19 Jimenez L, Mendez C. Which attention is needed for implicit sequence learning? *J Exp Psychol Learn Mem Cogn.* 1999;25:236–259.

20 Maxwell JP, Masters RSW, Eves FF. The role of working memory in motor learning and performance. *Conscious Cogn.* 2003;12:376–402.

21 Masters RSW, Maxwell JP. Implicit motor learning, reinvestment and movement disruption: what you don't know won't hurt you? In: Williams AM, Hodges NJ, eds. *Skill Acquisition in Sport: Research, Theory and Practice.* London, United Kingdom: Routledge; 2004: 207–228.

22 Hardy L, Mullen R, Jones G. Knowledge and conscious control of motor actions under stress. *Br J Psychol.* 1996;87:621–636.

23 Liao C-M, Masters RSW. Analogy learning: a means to implicit motor learning. *J Sport Sci.* 2001;19:307–319.

24 Maxwell JP, Masters RSW, Eves FF. From novice to know-how: a longitudinal study of implicit motor learning. *J Sport Sci.* 2000;18: 111–120.

25 Maxwell JP, Masters RSW, Kerr E, Weedon E. The implicit benefit of learning without errors. *Q J Exp Psychol A.* 2001;54:1048–1059.

26 Masters RSW. Theoretical aspects of implicit learning in sport. *Int J Sport Psychol.* 2000;31:530–541.

27 Orrell AJ, Eves FF, Masters RSW. Implicit motor learning of a balancing task. *Gait & Posture.* In press.

28 Fasotti L, Kovacs F. Slow information processing and the use of compensatory mechanisms. In: Chamberlain MA, Neumann V, Tennant A, eds. *Traumatic Brain Injury Rehabilitation Service, Treatments and Outcomes.* London, United Kingdom: Chapman & Hall; 1995:141–152.

29 Stapleton T, Ashburn A, Stack E. A pilot study of attention deficits, balance control and falls in the subacute stage following stroke. *Clin Rehabil.* 2001;15:437–444.

30 Fourneret P, Jeannerod M. Limited conscious monitoring of motor performance in normal subjects. *Neuropsychologia.* 1998;36:1133–1140.

31 Exner C, Weniger G, Irle E. Implicit and explicit memory after focal thalamic lesions. *Neurology.* 2001;57:2054–2063.

32 Gómez-Beldarrain M, García-Moncó JC, Rubio B, Pascual-Leone A. Effect of focal cerebellar lesions on procedural learning in the serial reaction time task. *Exp Brain Res.* 1998;120:25–30.

33 Pohl PS, McDowd JM, Filion DL, et al. Implicit learning of a perceptual-motor skill after stroke. *Phys Ther.* 2001;81:1780–1789.

34 Folstein MF, Folstein SE, McHugh PR. "Mini-Mental State": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res.* 1975;12:189–198.

35 Bamford J, Sandercock P, Dennis M, et al. Classification and natural history of clinically identifiable subtypes of cerebral infarction. *Lancet.* 1991;337:1521–1526.

36 Baddeley AD. *Working Memory.* Oxford, United Kingdom: Clarendon Press; 1986.

37 Cumming RG, Salkeld G, Thomas M, Szonyi G. Prospective study of the impact of fear of falling on activities of daily living, SF-36 scores, and nursing home admission. *J Gerontol A Biol Sci Med Sci.* 2000;55: M299–M305.

38 Forster A, Young J. Incidence and consequences of falls due to stroke; a systematic inquiry. *BMJ.* 1995;311:83–86.

39 Nyberg L, Gustafson Y. Patient falls in stroke rehabilitation: a challenge to rehabilitation strategies. *Stroke.* 1995;26:838–842.

40 Berg K, Wood-Dauphinee S, Williams J, Maki B. Measuring balance in the elderly; validation of an instrument. *Can J Public Health.* 1992;2(suppl):S7–S11.

41 Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: a review and critical appraisal. *Psychonomic Bulletin.* 1984;95:355–386.

42 Knopman DS, Nissen MJ. Procedural learning is impaired in Huntington's disease: evidence from the serial reaction time task. *Neuropsychologia*. 1987;29:245–254.

43 Brandimonte MA, Hitch GJ, Bishop DVM. Influence of short-term memory codes on visual image processing: evidence from image transformation tasks. *J Exp Psychol Learn Mem Cogn*. 1992;18:157–165

44 Brandimonte MA, Hitch GJ, Bishop DVM. Verbal recoding of visual stimuli impairs mental image transformations. *Mem Cognit*. 1992;20:449–455.

45 Brandimonte MA, Gerbino W. Mental image reversal and verbal recoding: when ducks become rabbits. *Mem Cognit*. 1993;21:23–33.

46 Schooler JW, Engstler-Schooler TY. Verbal overshadowing of visual memories: some things are better left unsaid. *Cognit Psychol*. 1990;22:36–71.

47 Cleermans A. *Mechanisms of Implicit Learning: Connectionist Models of Sequence Processing*. Cambridge, Mass: MIT Press; 1993.

48 Gentile AM. Implicit and explicit processes during acquisition of functional skills. *Scand J Occup Ther*. 1998;5:7–16.

49 Dettmann MA, Linder MT, Sepic SB. Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. *Am J Phys Med*. 1987;66:77–90.

50 Howell DC. *Statistical Methods for Psychology*. 2nd ed. Boston, Mass: PWS-Kent Publishing Co; 1987.

51 Baumeister RF. Choking under pressure: self-consciousness and paradoxical effects of incentives on skillful performance. *J Pers Soc Psychol*. 1984;46:610–620.

52 Masters RSW, Polman RCJ, Hammond NV. "Reinvestment": a dimension of personality implicated in skill breakdown under pressure. *Journal of Personality and Individual Differences*. 1993;14:655–666.

53 Dean CM, Shepherd RB. Task-related training improves performance of seated reaching tasks after stroke. *Stroke*. 1997;28:722–728.

54 Masters RSW, MacMahon KMA, Pall HS. Implicit motor learning in Parkinson's disease. *Rehab Psychol*. 2004;49:79–82.

55 Wilson BA, Baddeley A, Evans J, Shiel A. Errorless learning in the rehabilitation of memory impaired people. *Neuropsychol Rehabil*. 1994;4:307–326.

56 Hunkin NM, Squires EJ, Parkin AJ, Tidy JA. Are the benefits of errorless learning dependent on implicit memory? *Neuropsychologia*. 1998;36:25–36.

57 Graf P, Schacter DL. Implicit and explicit memory for new associations in normal and amnesic subjects. *J Exp Psychol Learn Mem Cogn*. 1985;11:501–518.

Appendix.

Bamford Classification of Stroke[35]

Classification	% of Strokes	Site of Infarct[a]	Signs and Symptoms
Total anterior circulation (TAC)	20	Occlusion of proximal MCA or ICA Volume of infarction > LAC or PAC Ischemia in superficial and deep territories of MCA ACA territory also may have infarcts	Weakness (±/or sensory deficit) of at least 2 of 3 body areas (face/arm/leg) Homonymous hemianopia Higher cerebral dysfunction (dysphasia, dyspraxia most common)
Partial anterior circulation (PAC)	35	Occlusion of branches of MCA Few ACA infarcts	2 of 3 TAC criteria or restricted motor or sensory deficits (eg, 1 limb, face, and hand, or higher cerebral dysfunction alone)
Lacunar (LAC)	20	Small infarcts in basal ganglia or pons	Pure motor—complete or incomplete weakness of 1 side, involving the whole of 2 of 3 body areas (face/arm/leg); sensory symptoms, including dysarthia or dysphasia Pure sensory—sensory symptoms, signs, or both, same distribution as motor Sensorimotor—combination of above Ataxic hemiparesis—hemiparesis and ipsilateral cerebellar ataxia
Posterior circulation (POC)	25	Affects brain stem, cerebellar, or occipital lobes	Frequently complex presentation; may include: • Bilateral motor or sensory deficits • Disordered conjugate eye movement • Isolated homonymous hemianopia • Ipsilateral cranial nerve palsy with contralateral motor or sensory deficit • Coma • Disordered breathing • Tinnitus • Vertigo • Horner syndrome

[a] MCA=middle cerebral artery, ICA=internal carotid artery, ACA=anterior cerebral artery.