Explicit Information Interferes with Implicit Motor Learning of Both Continuous and Discrete Movement Tasks After Stroke

Lara A Boyd, PT, PhD; Carolee J Winstein, PT, PhD, FAPTA

ABSTRACT
A large portion of the rehabilitation experience after stroke relies on implicit learning. However, our understanding of how best to facilitate motor learning after stroke is limited by a paucity of research that has explored the interaction between explicit information and implicit learning across various task domains. Previously we reported that the delivery of explicit instructions disrupted implicit motor learning after stroke that involved the sensorimotor cortical areas or basal ganglia. The purpose of this study was to determine the robustness of these findings by determining whether they could be replicated with 2 motor tasks, one discrete and one continuous, employed by the same group of participants. Ten individuals with stroke in the sensorimotor cortical areas (SMC), 10 with stroke in the basal ganglia (BG), and 10 age-matched healthy controls (HC) participated in this study. Each completed 3 days of practice of both a discrete implicit motor task (the serial reaction time task) and a continuous motor task (the continuous tracking task); all returned on a fourth day for retention tests. By random designation, participants were divided into either the explicit information (EI) or no explicit information (No-EI) groups. Consistent with previous results, we found that the response to explicit information after stroke was uniformly negative regardless of task or lesion location; both stroke groups demonstrated an interference effect of explicit information while the healthy control group did not. Strengthening these findings is the fact that the interference effect of explicit information was not task dependent. This point is particularly important for rehabilitation scientists as they instruct clients during various therapeutic tasks after stroke. Our data suggest that certain forms of explicit information delivered before task practice may not be as useful for learning as discovering the solution to the motor task with practice alone, and this is regardless of the type of task being learned.

Key Words: stroke, motor, implicit learning, explicit information, human, continuous, discrete

INTRODUCTION
Learning new, and re-learning old, motor skills consumes the largest portion of time in the rehabilitation process after stroke. Attempts to facilitate implicit motor skill learning, physical therapists spend considerable time providing explicit instructions focused on ‘how to’ perform movement tasks. Despite our clinical reliance on explicit instructions during motor skill rehabilitation there is mounting evidence that this type of information does not aid and may even hinder implicit learning after stroke. To date, no research has unequivocally established that verbal explicit instructions aid implicit motor skill learning in any population. In fact, we have previously reported an interference effect of explicit information during implicit motor learning after both sensorimotor and basal ganglia stroke. The current study sought to extend our earlier work by ascertaining whether explicit information (EI) might act differently for a continuous versus discrete motor task in persons post-stroke localized in either the sensorimotor cortical (SMC) regions or basal ganglia (BG).

LEARNING AND MEMORY: EXPLICIT VERSUS IMPLICIT
Learning and memory are not singular functions and can be subdivided into 2 main categories representing explicit and implicit processes. Explicit learning may be assessed directly by testing conscious, verbalizable knowledge of facts and events. In addition, explicit memories may be formed in as little as one exposure to new information. In contrast, implicit learning may only be inferred from observation of performance by changes in skilled behavior. In the case of implicit memory, any change in motor ability relative to baseline performance is assumed to reflect the acquisition of knowledge about the task, or motor learning. Implicit memories form much more slowly than do explicit ones, accumulating with large amounts of practice and often without conscious recollection of what elements of performance are being learned. The most often cited ‘real-world’ example of implicit motor learning is bicycle riding. As you practice riding a bike, improved performance is manifested by fewer falls, yet the ability to explicitly express ‘what’ procedures are being used to avoid falling is almost impossible.

Implicit and Explicit Learning: Do they Interact?
Physical therapists who deliver instructions regarding ‘how to’ move are assuming that the explicit and implicit learning and memory systems interact to share information. However, one of the most interesting features of the explicit and implicit learning and memory systems is their neural biological isolation from one another. This dissociation has been demonstrated both neuroanatomically and functionally. The explicit system is mediated by the hippocampus and adjacent medial temporal lobe structures, which owing to their focal nature may be completely destroyed by certain kinds of damage or disease. In contrast, the implicit system is highly distributed making it nearly impossible to completely disrupt. Despite their neuroanatomic

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separation, there is evidence that explicit and implicit memories sometimes develop in parallel, and may affect one another. These data raise the possibility that the explicit system might be used to stimulate or inform implicit learning. However, more recent evidence suggests that the implicit and explicit systems may actually compete for neural resources during learning. If this is the case, then the provision of some forms of explicit information during implicit motor learning may actually hinder or disrupt the formation of new motor memories.

Indeed we have previously reported that explicit information disrupted implicit motor sequence learning following sensorimotor cortical region stroke and also after focal basal ganglia stroke. We believe that the interference effects that we have documented indicate that explicit information may be less helpful in the development of the motor plan than is discovering a motor solution through practice and relying primarily upon the implicit system. This interference effect may be due to the increased demand placed on working memory by explicit information in combination with disrupted neuroanatomic and physiologic connectivity between the prefrontal cortex and network of motor regions.

The main goal of the present study was to confirm our previous findings that after stroke explicit instructions interfere with implicit learning, and determine whether specific task domains (i.e., discrete versus continuous movements) modify this finding.

**TASK DOMAINS: CONTINUOUS VERSUS DISCRETE MOVEMENTS**

Discrete movements are those with a defined beginning and end. For the current research we used the well-known serial reaction time (SRT) task to consider implicit learning of sequential discrete movements. During the SRT task, individuals respond by pushing a key as fast as possible in response to the appearance of matched stimuli on a computer screen. In contrast, continuous tasks are those that have no recognizable beginning or end; behavior continues until some factor arbitrarily stops it. Previously, a continuous tracking (CT) task has been adapted as an experimental paradigm for the study of continuous implicit motor sequence learning. During the CT task participants track a cursor as it moves across the screen. Unknown to participants, during both the SRT and CT tasks periods of repeating and random sequences of responses are practiced. The difference between performance during random and repeated sequences indexes implicit motor learning.

The dissociation between discrete and continuous movements can be framed in terms of how motor goals are conceptualized and represented. The timing and control of discrete movements may be considered as constructed by a series of periodic events that are demarked by salient events that frame each cycle. Others have hypothesized that owing to the well defined nature of discrete tasks that they are timed explicitly, as individual on and off actions. Thus, discrete movements may have an additional motor control requirement that mandates the programming of transitions between onset and offset events. In contrast, continuous movements may be conceptualized and represented as emerging as the task proceeds, and are thus more implicitly controlled. Though the above distinctions come largely from literature investigating timing, we decided to extend this research and capitalize on the potential differences between continuous and discrete tasks to ascertain how each is impacted by the provision of explicit information.

Thus, the purpose of this study was to determine if there is an interaction between implicit motor-sequence learning, explicit instructions, lesion location, and task type. We sought to address 2 main questions. First, does explicit information influence performance and learning similarly or disparately during practice and learning of continuous versus discrete implicit motor tasks? Second, we asked whether our findings would differ as a result of lesion location. Based on our previous work, we expected that both the SMC and BG groups would show an interference effect of explicit knowledge across both tasks.

**MATERIALS AND METHODS**

**Participants**

Ten individuals with unilateral stroke affecting the basal ganglia (BG) and 10 people with unilateral sensorimotor cortical stroke (SMC) were recruited; each stroke was characterized as chronic (> 6 months post-onset). In addition, 10 age-matched volunteers without any brain damage served as a healthy control (HC) group. All participants were right hand dominant (determined by participant self-report) and did not present with any evidence of dementia (26 or greater on the Mini-Mental State exam).

Participants were excluded if they had any acute medical conditions, uncorrected vision loss, previous history of psychiatric admission, history of multiple strokes, transient ischemic attacks, or extensive cortical white matter disease. Individuals with stroke were recruited from the outpatient clinical services at the University of Southern California Healthcare Consultation Center, Rancho Los Amigos National Rehabilitation Center, and the South Bay Stroke support group. Individuals in the healthy control group were recruited from the local community. The rights of all participants were protected by the Human Subjects Committee at the University of Southern California and Rancho Los Amigos National Rehabilitation Center; each signed an approved institutional informed consent form as well as a medical records release form prior to enrollment.

By random designation, participants were divided into either the explicit information (EI) or no explicit information (No-EI) groups. There were no significant differences in age, education, MMSE, or Fugl-Meyer scores between groups (Table 1).

**Lesion Location**

Prior to inclusion in this study an existing magnetic resonance image or computed tomography scan was obtained with written consent, and used to confirm a stroke affecting the basal ganglia or sensorimotor cortical regions. To illustrate the extent of damage each lesion was reconstructed using MRTcro software. Damaged regions were transformed onto a standard template which allowed the overlap of individual lesions into group data. Because side of lesion was not a variable of interest, we normalized all lesions to the left and overlaid them (Figures 1 and 2). For the basal ganglia group, the focus of overlap for both BG EI and BG No-EI groups was the putamen (Figure 1). For the sensorimotor stroke group lesion analysis revealed that the focus of stroke was a broad area including the sensorimotor cortical areas for both SMC EI and SMC No-EI (Figure 2).
General Procedures

All subjects practiced both the serial reaction time (SRT)\(^2\) and continuous tracking (CT)\(^2,28\) tasks. For all responses individuals in the BG or SMC groups used the less-affected or hand ipsilateral to brain damage for all responses; individuals in the HC group were matched for hand use (Table 1). The order of task practice was counterbalanced across participants.

The same procedures and task practice structure were followed for both tasks. Participants practiced 50 trials (5 blocks; 10 trials/block) of both tasks each day under identical conditions. This procedure was repeated for 3 days (150 trials total) to ensure adequate acquisition practice.\(^2,22,26\) To better separate performance effects from more permanent changes in behavior associated with learning, a retention test was completed on a fourth day.

Table 1. Participant Characteristics. Age in years. Post-stroke duration is in months. MMSE = Mini-Mental Status Exam. sd = standard deviation. BG = basal ganglia. SMC = Sensorimotor cortex. EI = explicit information. *Upper Extremity Fugl-Meyer Motor Score, 66=maximum.

<table>
<thead>
<tr>
<th></th>
<th>Sex</th>
<th>Age (sd)</th>
<th>MMSE (sd)</th>
<th>Post-Stroke Duration (sd)</th>
<th>Fugl-Meyer Motor* (sd)</th>
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<tbody>
<tr>
<td>Basal Ganglia Lesion Side</td>
<td></td>
<td></td>
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<tr>
<td>BG EI</td>
<td>4 Right, 1 Left</td>
<td>4 Male, 1 Female</td>
<td>51.0 (9.8)</td>
<td>28 (1.4)</td>
<td>27.8 (28.2)</td>
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<td>BG No-EI</td>
<td>4 Right, 1 Left</td>
<td>3 Male, 2 Female</td>
<td>58.2 (14.6)</td>
<td>28.4 (1.1)</td>
<td>10.4 (5.6)</td>
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<td>Sensori-motor Lesion Side</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SMC EI</td>
<td>3 right, 2 left</td>
<td>2 male, 3 female</td>
<td>59.0 (10.5)</td>
<td>29.0 (1.2)</td>
<td>33.4 (18.9)</td>
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<td>SMC No-EI</td>
<td>1 right, 4 left</td>
<td>4 male, 1 female</td>
<td>58.6 (19.2)</td>
<td>27.8 (1.8)</td>
<td>48.0 (30.1)</td>
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<tr>
<td>HC EI</td>
<td>3 Right, 2 Left</td>
<td>1 Male, 4 Female</td>
<td>55.4 (11.0)</td>
<td>29.8 (0.4)</td>
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</tr>
<tr>
<td>HC No-EI</td>
<td>3 Right, 2 Left</td>
<td>2 Male, 3 Female</td>
<td>57.4 (16.1)</td>
<td>29.6 (0.5)</td>
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</table>

Figure 1. Representations of basal ganglia strokes reconstructed by transcribing lesions from MRI or CT scans onto axial templates.\(^\text{36}\) All lesions were reconstructed on the left for illustration purposes. The focus of overlap for the BG EI group (A) was in the putamen; the focus of overlap for the BG No-EI group (B) was also in the putamen.
Tasks

Serial Reaction Time Task

For SRT task practice 4 different colored circles (yellow, red, blue, and green) could be displayed on the computer screen (17 inch, color) placed directly in front of the subject. A standard keyboard was placed on the table directly in front of the computer screen with the most centered letters (‘v, b, n, and m’) capped with the colors yellow, red, blue, and green. Displaying 1 of the 4 colored circles on the screen generated the stimuli for movement. Only one colored circle appeared at a time; the other circles were transparent, however, each colored circle always appeared in the same location, and thus maintained its relative location on the screen. Responses were made by pressing 1 of the 4 keys corresponding (in color and location) to the appropriately colored circle. As soon as the correct key was pushed, the next stimuli for movement appeared. However, the stimuli for movement remained on the screen until the correct response was made. A custom computer software program (L. Boyd, 2001, E-Prime software platform, version Beta 5.0, Psychology Software Tools Inc, Pittsburgh, PA) controlled the appearance of the colored circles and recorded subjects’ responses. Time (response time; RT) and accuracy were stored after every key-press for off-line analysis. Participants in all groups were highly accurate in their responses (>90% correct); thus, this measure was not included in our data analyses.

Subjects were seated facing the computer screen with their ipsilesional (stroke) or matched (control) hand resting on the keyboard. Minimal excursion was required for responses as participants made key-presses with 1 of 4 fingers (index through little finger), which they were allowed to lightly rest on the colored keys. All subjects practiced the same 10-element ambiguous repeating sequence (Blue-Yellow-Red-Blue-Green-Red-Blue-Red-Green-Yellow; each time through the 10-element sequence = 1 sequence trial). During each practice session for the SRT task, an initial block of random responses were practiced (1 block = 100 individual responses or 10 trials). Next, 4 blocks of repeating-sequence practice and a second block of random responses were performed. Finally, participants practiced 1 last block of the repeating sequence. This practice pattern (1 random block, 4 sequence blocks, 1 random block, 1 sequence block) was repeated on 3 consecutive days. On day 4, retention tests were given to assess learning of the SRT task. Retention was measured by performance of 1 block of the repeating sequence. Instructions to respond “as fast and accurately as possible” were given daily to all participants.

Continuous Tracking Task

A lightweight lever was attached to a frictionless vertical axle, and secured to a table parallel to the floor. A linear potentiometer attached to the transducer at the base of the vertical axle recorded the analog signal that was converted to digital by a National Instruments A/D board (shielded multifunction I/O board, #PCI-6024E) and sampled at 200 Hz.

A target cursor (in white) was visible on a black background as it moved from left to right across the screen (30 seconds total; 1.1 cm/sec; LabView software; National Instruments, Corp, Austin, Tex). The task was to track the vertical path of the target with movements of the lever. Participants sat in front of the monitor with their arm resting on the lever and made arm motions from 0° to approximately 90° of internal rotation with the start position at 45°; participant movements appeared as a green cursor; thus,
participants saw their responses on the screen in relation to the target.

Unknown to the participants, the middle third of each tracking pattern was repeated and identical across practice and retention. This pattern was constructed using the polynomial equation as described by Wulf and Schmidt (1997) with the following general form:

\[ f(x) = b_{o} + a_{1} \sin(x) + b_{1} \cos(x) + a_{2} \sin(2x) + b_{2} \cos(2x) + \ldots + a_{6} \sin(6x) + b_{6} \cos(6x) \]

The middle (repeated) segment was constructed by using the same coefficients for every trial. The first and third segments of the tracking pattern were generated randomly using coefficients ranging from 5.0 to -5.0. A different random sequence was used for both the first and third segments for every trial. However, to ensure uniformity the same random tracking patterns were practiced by all of the participants. In each third of the tracking pattern there were 10 separate reversals in the direction of internal or external shoulder rotation. The trajectories of the target and participants' movements did not leave a trail on the screen and thus, participants could not visualize the entire target pattern. Instructions to track ‘as accurately as possible’ were given daily.

Experimental Manipulation of Explicit Information

Explicit Information Groups: Across the 3 days of practice, participants in the EI groups were progressively given explicit information of the task. On day 1, no explicit information was provided. Explicit knowledge was tested at the conclusion of practice day 1 for all EI participants. At the beginning of day 2, participants were explicitly instructed that there was a repeating element to some of their responses. From this point forward all participants in the EI groups subjectively knew of the repeating sequence. Explicit knowledge (recognition memory) was tested again at the end of practice day 2. At the beginning of day 3, participants were explicitly informed of the location and composition of the SRT and CT sequences using a pictorial representation of the repeating sequence. This was done separately for both tasks. Participants were asked to study, without physically practicing, the picture representations of the sequences. A pretest of explicit knowledge (recognition memory) was administered when participants indicated readiness (participants took 5 to 10 minutes to study). Following practice on day 3, explicit knowledge was reassessed. On retention test day 4, no explicit instructions or reminders were provided. These experimental manipulations are summarized for each group and day in Table 2.

No-Explicit Information Groups: In contrast, participants in the No-EI groups were asked to respond/track as accurately as possible and not give any indication of the existence of the repeating sequence. If they verbalized having noticed or asked about a sequence, the investigator remained neutral, providing no direct answer or response. Assessment of explicit knowledge occurred at the conclusion of day 4, after completion of the retention test.

Explicit Testing

Explicit knowledge was tested separately for both tasks. Two levels of explicit knowledge were tested: (1) subjective awareness of the existence and composition of the sequence, and (2) recognition memory. Subjective memories were tested by asking subjects if they ‘noticed anything about the task?’ Recognition memory tests were used to determine if participants would be able to correctly identify the repeated sequence after watching it on the screen. Ten trial sequences were shown to all participants; 3 of the practiced repeating sequence, and 7 foils. Participants were asked to judge whether they had previously seen each sequence as it was played. Testing of subjective explicit awareness of the repeating sequence occurred on day 1 for the EI groups and on day 4 for the No-EI groups. Table 3 provides the instructions and details of explicit testing.

Outcome Measures

SRT Task: Different outcome measures were calculated for the SRT and CT tasks. For the SRT task the primary outcome measure was response time (RT; reaction plus movement time), which was calculated as the time between stimulus onset to completion of the response. Response time was stored for each trial. As is standard

<table>
<thead>
<tr>
<th>Table 2. Explicit Information and Knowledge Testing Conditions by Explicit Information (EI) Group and Day</th>
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<tbody>
<tr>
<td><strong>Group</strong></td>
</tr>
<tr>
<td>EI</td>
</tr>
<tr>
<td>Explicit knowledge test</td>
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<tr>
<td>No-EI</td>
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<tr>
<td>Explicit knowledge test</td>
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</table>

\[ b_{o}=2.0, a_{1}=-4.0, b_{1}=3.0, a_{2}=-4.9, b_{2}=-3.6, a_{3}=3.9, b_{3}=4.5, a_{4}=0.0, b_{4}=1.0, a_{5}=-3.8, b_{5}=-0.5, a_{6}=1.0, \text{ and } b_{6}=2.5 \]
procedure in SRT-type task data analyses, we calculated the median RT for each 10-element sequence trial. Calculation of median RT values for each sequence trial reduces the sensitivity of this measure to very large or small values. Response times were then summarized by calculating the mean median for each block of responses. This procedure was performed for both random and repeated sequences and represents absolute RT.

**CT Task**: CT task performance was measured using root mean squared error (RMSE) which reflects overall tracking errors in the kinematic pattern and is the average difference between the target pattern and participant movements. This score was calculated separately for random and repeating segments on every 60 s tracking trial and averaged by block (every 10 trials).

To allow comparison across the 2 different tasks a percent change score was calculated (Repeted RT or RMSE / Random RT or RMSE X 100). This score reflects how much faster or more accurate performance was for the repeated as compared to the random sequences of movement. For example, a score of 80% indicates that performance on the repeating sequence was faster (RT) or more accurate (RMSE) than that seen during random sequences. Lower scores indicate more change during repeated sequences relative to random ones; hence a percent change score of 80% would reflect superior performance during acquisition and implicit learning at retention. This calculation was made for each practice block for both tasks using repeated sequence data (RT or RMSE) and the mean median RT or RMSE from the second random sequence block from day 1 of practice. Early in practice, RT or RMSE are often very long but rapidly improve as subjects become familiar with the task. Improved performance for random sequences can be attributed to nonspecific learning about the kinematic pattern and is the average difference between the target pattern and participant movements. This score was calculated separately for random and repeating segments on every 60 s tracking trial and averaged by block (every 10 trials).

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Explicit knowledge was evaluated by calculating a percent correct score for subjective and recognition memory (e.g. 87% or 14 of 16 participants recognized the repeating sequence).

### Statistical Analyses

To test our hypotheses that explicit information would benefit explicit motor sequence learning for discrete tasks after stroke we performed a Group (HC, SMC, BG) by Task (SRT, CT) by Information (EI, No-EI) by Block (1-15) Analysis of Variance (ANOVA) with repeated measures correction using percent change as our dependent measure. Follow-up analyses separately considered the impact of explicit information (Group X Task X Block ANOVA with repeated measures correction) and different group responses to the presence or absence of explicit information (Information X Block ANOVA with repeated measures correction) with percent change scores collapsed across tasks. Retention test data from Day 4 were evaluated with a multivariate Group by Information by Task ANOVA.

Explicit knowledge for both tasks was assessed using a multivariate Group by Information ANOVA with subjective awareness and recognition memory scores for the 2 tasks as dependent measures. Data from the last set of explicit knowledge tests (post practice on day 3 for the EI groups; post retention test on day 4 for the No-EI groups) were used for this analysis. In all of these analyses the level of significance was set at p ≤ .05. Secondary analyses were performed after the omnibus ANOVA. All statistical analyses were performed using SPSS 13.0 (SPSS, Inc, Chicago, Ill).

### RESULTS

The results of our primary analysis (Group X Task X Information X Block ANOVA) demonstrated significant differences across the multiple conditions in this investigation (F(2,30) = 4.065, p = .030). Importantly, a main effect of Block demonstrated that regardless of information condition or task all participants improved their performance with practice (F(1,15) = 18.522, p = .000; Figure 3). Task differences were also apparent as evidenced by a main effect of task (F(1,39) = 19.492, p = .000; Figure 3). To more carefully parcel out the effects of task and information on the groups’ performance we performed several follow-up analyses to consider these factors separately.

### Information Effects

Our analysis of information effects demonstrated that after stroke explicit information acted similarly on both continuous and discrete tasks. A significant Group by Task By Block ANOVA

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Table 3. Explicit Knowledge Test Conditions and Questions

<table>
<thead>
<tr>
<th>Explicit Test Condition</th>
<th>Explicit Test Questions</th>
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<tbody>
<tr>
<td>Subjective awareness</td>
<td>“Did you notice anything about the task?” If yes, “What was it?” If no, “There was a repeating sequence. Can you tell me what it was?”</td>
</tr>
<tr>
<td>Recognition memory</td>
<td>Watch 3 sequences: 1 True 2 False “Is this a sequence that you recognize?”</td>
</tr>
</tbody>
</table>

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$MSE = \sum_{i=1}^{n} (x_i - T_i)^2 / n^{1/2}$

$x_i =$ participant’s position in degrees at time 1, $T_i =$ target position at time 1, $n =$ the number of samples for the participant’s trajectory array
for the EI groups (F(2,12) = 3.900, p = .050) revealed that HC
and stroke groups responded differently to the presence of explicit
information. Post-hoc tests showed that the locus of this difference
was between the HC and 2 stroke groups. Specifically, explicit
knowledge aided the performance of the HC group for both tasks
and hindered performance of both groups with stroke (HC EI vs.
SMC EI p = .010; HC EI vs. BG EI p = .013). The performance
of the 2 stroke groups (SMC EI and BG EI) was similar (p = .727).
The negative effect of explicit information was noted for
performance of both continuous and discrete tasks (Figure 3). In

Figure 3. Acquisition phase and retention data collapsed across
tasks. All data a represented as percentage change in sequence
performance as compared to random performance; lower scores
represent more change (ie, learning). The line at 100% reflects
performance for random sequences. EI data are shown in open
triangles, No-EI data are in closed circles.
(A) Healthy control data demonstrate a beneficial effect of EI
across acquisition and at retention.
(B) Sensorimotor cortical area stroke data show an interference
effect of EI for both acquisition and at retention.
(C) Basal ganglia stroke participants also demonstrated
a negative response to EI. This was maintained at retention.

Figure 4. Retention test data for all groups shown as percentage
change by EI condition for both tasks. Note the uniform
response to EI condition regardless of task or group. The line
at 100% reflects performance for random sequences. Lower
scores reflect more change at retention.
(A) The healthy control groups benefited from EI regardless
of task.
(B) Sensorimotor cortical area stroke showed less change
when provided with EI than when not for both tasks.
(C) The basal ganglia groups retention test performance was
negatively affected by EI for both tasks.
contrast, the performance of the three No-EI groups did not differ (p = .779).

Effects of Task: Continuous versus Discrete
The only task effects noted in this study were the result of larger improvements made for the CT as compared to the SRT task. When separately evaluated by task (Group X Block ANOVA) the groups behaved differently for both the continuous CT task (F(2,27)=6.693, p=.004) and discrete SRT task (F(2,27) = 4.040, p = .029). The locus of this difference was again the disparate response of the HC EI group as compared to the SMC EI and BG EI groups that were evident at retention.

The demonstration of similar performance across continuous and discrete tasks allowed us to collapse across task and carefully consider the impact of explicit information separately for each group. In each case we found significant Block by Information interactions (HC F(1,8) = 3.120, p = .050; SMC F(1,8) = 3.931, p = .050; BG F(1,8) = 7.750, p = .024). Visual inspection of the data, however, demonstrates that this finding is due to the opposite effect of explicit information on the HC versus stroke groups (Figure 3).

Retention
Retention data demonstrated that implicit learning of both continuous and discrete tasks was disrupted by explicit information for the stroke groups but not the healthy controls (Group X Information multivariate ANOVA; F(2,29) = 4.143, p = .028). This finding indicates that the interference effect that explicit information stimulated in individuals with stroke was relatively permanent and retained at retention in the absence of any further instructions (see Figure 4). In contrast, the benefit of instructions for healthy control participants was maintained at the retention test.

Explicit Knowledge
Consideration of differences in explicit knowledge between the groups and across information conditions demonstrated main effects of explicit information (F(1,24) = 12.059, p = .002) and group (F(2,24) = 3.000, p = .050). These data are the result of the EI groups’ ability to demonstrate more explicit knowledge than the No-EI groups. In addition, the HC group gained more explicit knowledge that the other groups (Tables 4 & 5).

DISCUSSION
In this work we found that the response to explicit information after stroke is uniformly disruptive regardless of task or lesion location. Based on current theories of timing control of discrete movements, we had expected that explicit information might benefit implicit learning of discrete tasks, such as our SRT task. However, we found remarkable consistency across our tasks in that both stroke groups demonstrated an interference effect of explicit information. This point is particularly important for rehabilitation scientists who instruct clients during therapeutic tasks after stroke. Our data suggest that explicit information delivered before task practice is not as useful as discovering the solution to the motor task through practice alone.

Despite the interference effect that explicit information stimulated in individuals with stroke, it is important to note that all groups demonstrated implicit learning for both tasks (see Figure 4). A more precise interpretation of our data reveals that explicit information slowed or disrupted implicit learning; however, implicit learning was not arrested by the provision of explicit information. Of note is the improvement in performance seen for the BG-EI and SMC-EI groups when explicit information was not provided at the retention test (see Figure 3 difference between last block on day 3 and retention test).

Task does not Matter?
We were surprised that no differences were noted when we compared implicit learning of continuous and discrete tasks. We expected that our discrete task might be more susceptible to the influence of explicit instructions. Previous work investigating timing control proposed that discrete tasks rely on a precise, event timing system where the brain possesses an explicit representation of the timed intervals necessary for task completion.

Alternately, proponents of this event timing hypothesis suggest that continuous movements are indirectly timed and controlled by the use of emergent implicit strategies. Based on this previous work, it appeared plausible that discrete tasks would be more easily represented by explicit information and thus, performance and implicit learning might benefit from the acquisition of explicit knowledge. This assumption proved to be false. Not only did the BG-EI and SMC-EI groups not benefit from explicit instruction for the SRT task, but it actually induced an interference effect relative to that for the no-EI groups. Despite the HC-EI group’s superior performance when provided with explicit information for both tasks, less change was evident during the discrete SRT than the continuous CT task for this group. This finding may represent a floor effect of our SRT reaction time measure. However, we believe that a more likely explanation is that the effect of explicit information during implicit motor sequence learning is consistent across task types and not differentially impacted by discrete versus continuous motor behaviors.

Our results that task type (as manipulated here) does not matter as explicit information seems to act uniformly on implicit motor learning confirm and extend our past work. To our knowledge this is the first study to consider the differential effects of continuous and discrete tasks during implicit motor learning. Though in the current study we did not find an effect of task, we recently reported that choice of implicit motor task does influence learning in some instances. In this work, we discovered that stroke severity was a major factor in determining how well participants’ implicit motor performance improved during the practice of 2 discrete movement behaviors. In this case individuals with moderately severe strokes reacted uniformly to a functionally based implicit learning task and to the SRT. In contrast, healthy control participants and individuals with mild strokes showed more improvement on the functionally based task as compared to the SRT. The majority of participants in our current study had strokes that would be considered as moderately severe (using Fugl-Meyer scores, see Table 1). Because of their severity of stroke it is tempting to speculate that if we had tested a mildly affected group we might find differences between the CT and SRT tasks. We believe that this is unlikely, however,
Based on the pattern of performance of our healthy control group which was uniform across tasks and explicit information conditions (see Figure 4).

**Interference effect of Explicit Instructions**

As mentioned our current results are consistent with previous work that has demonstrated an interference effect of explicit information after stroke. In addition, we once again found that explicit information benefits age-matched healthy control participants. These effects were noted for the BG-EI and SMC-EI groups even though they did not demonstrate full explicit knowledge for the sequence, particularly for the CT task (Table 4). This finding suggests that even minimal explicit awareness may alter implicit learning. Previous work has demonstrated that manipulating explicit knowledge (directed attention) during practice changes performance. We have extended this finding, as in this case, providing explicit instructions to individuals with stroke altered both acquisition performance and retention test ability.

Because we distinguished performance acquisition (practice) from implicit motor learning using a defined retention test we are able to make important distinctions when considering the impact of explicit information on implicit learning. Employing a retention test (administered after a one-day delay) allowed us to determine whether the effect of explicit information had a transient or more permanent effect on learning. We found that the effect of explicit information was relatively permanent, noting that the difference between the EI and No-EI groups was maintained despite the withdrawal of explicit information at the time of the retention test. This suggests a robust effect of explicit information on implicit motor learning which may have clinical ramifications.

Our data are a part of an emerging theme in the motor skill learning literature suggesting that implicit and explicit learning can either be separated and operate in isolation or interact and influence one another. From these data and others it is becoming clear that the mixing of explicit and implicit is not necessarily beneficial for learning; in fact, it appears that after stroke in the basal ganglia or sensorimotor cortical regions it is at least temporarily harmful. Our demonstration of a detrimental effect of explicit instructions is not new, but only recently has this work begun to be extended into populations with neurologic damage. Poldrack et al has demonstrated that during learning the implicit and explicit systems may actually compete with one another for neural resources. These authors speculate that competition among memory systems may be due to incompatible demands during learning. The need for access to flexible knowledge maintained by the medial temporal lobe stands at odds with the necessity of fast, automatic responses supported by the striatum and motor cortex. Normally, this competition is managed by rapid, reciprocal patterns of activation in the medial temporal lobe, basal ganglia and motor cortex. Our data raise the possibility that damage to either a portion of the striatum or sensorimotor cortical regions disrupts this arbitration among memory systems and consequently impairs the usefulness of explicit information during implicit learning.

### Table 4. Explicit Knowledge of the EI groups. Subjective awareness of the sequence was assessed at the conclusion of the first day of practice. Recognition memory was tested post-study period and practice on day 3.

<table>
<thead>
<tr>
<th></th>
<th>SRT Task</th>
<th>CT Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjective % Noticed</td>
<td>Recognition % Correct</td>
</tr>
<tr>
<td>HC</td>
<td>60.0 (24.4)</td>
<td>93.2 (6.8)</td>
</tr>
<tr>
<td>BG</td>
<td>20.0 (20.0)</td>
<td>86.4 (8.3)</td>
</tr>
<tr>
<td>SMC</td>
<td>40.0 (24.4)</td>
<td>73.0 (12.6)</td>
</tr>
</tbody>
</table>

### Table 5. Explicit Knowledge of the No-EI groups assessed post-retention test on day 4.

<table>
<thead>
<tr>
<th></th>
<th>SRT Task</th>
<th>CT Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjective % Noticed</td>
<td>Recognition % Correct</td>
</tr>
<tr>
<td>HC</td>
<td>80.0 (20.0)</td>
<td>66.2 (10.6)</td>
</tr>
<tr>
<td>BG</td>
<td>20.0 (20.0)</td>
<td>46.4 (13.4)</td>
</tr>
<tr>
<td>SMC</td>
<td>20.0 (20.0)</td>
<td>52.8 (8.1)</td>
</tr>
</tbody>
</table>
Multiple Learning and Memory Systems

Regions within the SMC that are well understood to play a critical role in behavioral motor output include the primary motor cortex (M1), premotor cortex (PMC), and sensorimotor area (SMA). Ipsilateral M1 is active during the execution of complex, repetitive finger movements.\(^{53,54}\) Further, once explicit knowledge is gained for implicit motor behaviors neuroimaging shows that bilateral PMCs become active even during unimanual movements.\(^{55}\) This finding suggests that PMC has a strong role in regulating sequence production when learners have access to explicit information. The PMC has strong connections with prefrontal regions associated with explicit memories such as the dorsolateral prefrontal cortex (DLPFC) and is also reciprocally connected with the caudate nucleus of the basal ganglia.\(^{56,57}\) These neuroanatomic pathways appear to indicate that damage to the PMC and associated regions may disrupt the ability to integrate explicit information into implicit movements.

Similarly, the basal ganglia are richly connected with both motor cortical regions and the frontal cortex.\(^{57,58}\) At least 5 neuroanatomically distinct, reciprocal basal ganglia-thalamocortical circuits have been identified.\(^{59,60}\) It is assumed that these circuits allow the basal ganglia to have a widespread impact of the function of various cortical regions including the motor and prefrontal areas.\(^{58,60}\) The 'motor' circuit, which is comprised of the putamen, thalamus, SMA, and PMC, is thought to most directly affect movement.\(^{60,61}\) A separate 'complex' circuit has been identified that interconnects the caudate, thalamus, and DLPFC.\(^{58}\) The intricate complexity of the neuroanatomical interconnections between the motor and prefrontal cortex, and basal ganglia suggest that their combined action can facilitate high-level integrative functions. Our findings advance this conceptualization; we suggest that damage to the basal ganglia disrupted the interconnections with the prefrontal cortex that resulted in an inability to utilize explicit information during implicit motor learning.

Thus, we speculate that under normal circumstances, both the basal ganglia and the PMC are highly active to integrate explicit information into representations of movement (motor plans) as they are being learned. Our data suggest that disruption of either the basal ganglia or PMC results in an inability to benefit from explicit information during implicit motor learning.

The Ipsilesional Hemisphere

Normally, motor performance of one hand invokes activity in the contralateral sensorimotor areas.\(^{55}\) Thus, in the past it has been incorrectly assumed that stroke does not directly affect the ipsilateral hemisphere. In this study and in numerous others\(^{1,2,62,64,65}\) there have been significant demonstrations of disrupted motor output using the arm ipsilateral to stroke. As both the SRT and CT tasks were entirely unimanual our finding suggests that bilateral hemispheric activity is necessary for executing and learning implicit motor sequence plans. Our data also show that stroke negatively affects the ability to use explicit information during implicit motor task practice, even when using the ipsilesional upper extremity. As use of the ipsilesional arm invoked the undamaged hemisphere, the performance deficits we recorded strongly suggest that bilateral hemispheric function is necessary during implicit motor-sequence learning. We believe that these findings, along with others\(^{1,2,26,62,64,65}\) imply that therapeutic interventions must be directed to both the hemiparetic and the non-hemiparetic upper extremity after stroke.

CONCLUSIONS

Several conclusions may be drawn from our data. First, for healthy participants, explicit information appears to benefit implicit learning. Second, damage to the basal ganglia or sensorimotor cortex disrupts the capacity for explicit information to constructively influence the formation of an implicit motor plan over practice alone. Last, these findings were immune to the disparate demands of task domain (discrete or continuous). Our current data in combination with previous work lead us to believe that after stroke, some forms of explicit information are less helpful in the development of a motor plan than is discovering a motor solution through practice using the implicit system alone. Thus, the integrity of the basal ganglia and sensorimotor cortical areas may be crucial in determining the efficacy of explicit task information during implicit motor-sequence learning.

Clinical Implications

After stroke affecting the sensorimotor cortical areas or basal ganglia explicit information as provided here does not benefit implicit motor sequence learning regardless of the task domain. Because much therapeutic time is dedicated to motor skill acquisition after stroke this information is crucial for physical therapists that construct and implement conditions of practice and interventions designed to facilitate motor skill learning. It is likely that to optimize rehabilitation outcomes alternative methods of prescriptive information may be more useful to the learner than are explicit instructions. Other factors surrounding motor task performance for which there is growing evidence include focus of attention,\(^{60}\) visual feedback,\(^{60}\) extended practice,\(^{1,2,67}\) and success information.\(^{68-70}\) Clearly, exploring these alternate forms of explicit information and task conditions during implicit motor skill learning after stroke will be challenging for therapist and client alike, however, they may yield far more beneficial long-term results.

ACKNOWLEDGEMENTS

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Invited Commentary

Sheila Schindler-Ivens, PT, PhD

Look around nearly any rehabilitation gym, and you will likely find physical therapists cuing hemiparetic patients to take larger steps, put more weight on their paretic leg, or reach with their arm, not their trunk. As physical therapists, we spend a great deal of time verbally informing our patients about their movement deficits and coaching them to move more effectively. Is all this cuing necessary? Is it helpful?

In the preceding article, Drs. Boyd and Winstein provide evidence that, for people with stroke, less information may be more. The present paper is the most recent in a series of studies by the same authors examining the effect of explicit information on motor learning in chronic stroke survivors. In a series of elegantly designed experiments, the authors have demonstrated that explicit instructions may not enhance and may even impede motor learning after stroke. The present paper confirms and extends previous results by showing that explicit information interferes with learning a continuous as well as a discrete movement. Moreover, the effect is comparable in people with damage to either the basal ganglia or the sensorimotor cortex. Hence, there appears to be mounting evidence suggesting that, perhaps, physical therapists should minimize explicit instructions and allow our hemiparetic patients to solve movement problems experientially. However, as I am certain the authors would agree, before we stop providing cues to our patients with stroke, it is important to consider the applicability of Boyd and Winstein's findings to the real world environment.

To date, studies examining the usefulness of explicit information on motor learning post-stroke have employed motor sequencing tasks; whereby, volunteers practice producing a sequence of movements. These experimental tasks may share similarities with some real life scenarios such as learning to transfer from a wheelchair to bed, which involves several movements performed in a distinct order. The patient is taught to roll the wheelchair to the bed, lock the breaks, remove the footrest, scoot to the edge of the chair, and so on. Boyd and Winstein's work may suggest that explicit cuing is detrimental to this type of task as well as other skills that have sequential components such as dressing and bathing. The present study, which extends the authors' previous results to a continuous motor task, suggests that other continuous movements such as walking and propelling a wheelchair may be disrupted similarly by explicit instructions.

Despite important contributions to understanding post-stroke motor learning, Boyd and Winstein's work does not address other essential aspects of rehabilitation. The tasks employed in their studies may not be important or functionally relevant to people recovering from stroke. Participants were evaluated on their ability to respond to an arbitrary sequence of colors or to track a geometric pattern displayed on a computer screen. Unlike dialing a telephone or negotiating an escalator in a shopping mall, these tasks have limited functional implications and failure to succeed carries no adverse consequences. Hence, it is unclear whether similar results would be observed during functionally meaningful movements. Moreover, Boyd and Winstein's work has examined only the nonparetic or less affected arm of people with stroke. This approach is clever because it allows the experimenters to examine motor sequence learning in relative isolation, without confounding effects of weakness, spasticity, or muscle synergy. However, the paretic extremities are the chief target of physical therapy, and whether the present observations generalize to the paretic upper extremity or the lower limbs has not been demonstrated.

While considerable work remains to be done before we have a complete understanding of how to optimize motor re-learning post-stroke, Boyd and Winstein's work is provocative. It suggests that, perhaps, we should be selective in providing hemiparetic clients with explicit cues about motor performance, and we should be aware that not all motor tasks will be enhanced by explicit cues. Moreover, we should learn to recognize instances in our own patients in which explicit information interferes with motor performance and, when appropriate, replace verbal and visual cues with implicit motor learning experiences.

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Response to Schindler-Ivens Invited Commentary

Lara Boyd, PT, PhD; Carolee Winstein, PT, PhD, FAPTA

In the course of a therapeutic session, at least part of the encounter time is devoted to the provision of explicit instructions about the activity that is to be performed. In an effort to guide the learner to an optimal motor solution, these prescriptive instructions commonly are centered on ‘how to’ complete a movement task. Despite the time and effort directed to this ‘instruction’ element of treatment, few studies have considered the impact of explicit information on the learning of implicit motor skills.1-4 In fact, we are unaware of any studies that have established, unequivocally, that verbal explicit instructions are beneficial for implicit motor skill learning in any population, or for any task.

Our current work has extended our previous findings which demonstrated the limited value of explicit verbal instructions2,3 to both discrete and continuous laboratory tasks in individuals with basal ganglia and sensorimotor cortical stroke. However, as Dr. Schindler-Ivens cautions in her commentary, to date we have only used artificial laboratory tasks in our work. Therefore, it is unclear whether or not the results derived from our experiments can be generalized to other motor learning studies that use more ecologically valid movement tasks. Clearly, considering whether explicit instructions benefit or interfere with the motor learning of such functional skills as might be used in the clinical setting, is a logical next step in this line of inquiry. From a ‘bench to bedside’ approach to the design and testing of rehabilitation interventions, our work establishes the theoretical rationale and provides a proof of concept for future, clinically based research.

Why did we choose to use the ‘good’ arm for these studies and not the paretic limb that would be the focus of most therapies? We chose to test the less-affected (we know from previous research, that the ipsilesional limb is not normal), nonparetic upper extremity in our research in an effort to reduce the possibility that the impaired motor control expressed in the paretic limb might mask or lessen the learning-related changes we measure. Because we find significant motor sequence learning deficits after the provision of explicit instructions, even when testing the nonparetic arm and hand, we expect that our findings would only be magnified if the stroke-affected upper extremity were used. Though still speculation at this time, there is no scientific rationale for the hypothesis that our results might be different for another effector system or task such as would be expected with a lower extremity motor task.

We certainly do not want to suggest that all instructions impede learning. In fact we showed that explicit instructions disrupted but did not abolish implicit motor learning (See Figures 3B and C). We do believe that clinicians should be aware that some kinds of explicit information may not always be beneficial for motor learning. Indeed, other alternative methods of prescriptive information might be more effective for implicit motor skill learning such as directing attentional focus.5 Implementation of this idea into the clinical environment would require substantial re-conceptualization, at this time. For example, let’s suppose that explicit instructions were better used to focus the learner’s attention than to provide information about how to perform the task. Making such a paradigm shift in rehabilitation therapy may prove initially difficult for both clinician and patient, yet it may yield far more beneficial outcomes. Obviously, much more research is needed before we should exchange our current practices for revised and modified evidence-based approaches. Until then, we should remain thoughtful and continue to openly challenge much of the conventional wisdom that has guided our practice for so long.

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1University of Kansas Medical Center (lboyd@kumc.edu)
2University of Southern California
The Golden Synapse Award

The 2006 Golden Synapse was awarded to the article titled, *Explicit Information Interferes with Motor Learning of Both Continuous and Discrete Tasks after Stroke* authored by Lara Boyd PT PhD and Carolee Winstein PT PhD. The article was published in the June 2006 issue of *Journal of Neurologic Physical Therapy* (Volume 30, Number 2 pp 46-59). The award recognizes the most outstanding article published each year. The decision is made by *JNPT* Reviewers and Editorial Board members and is based on the article’s conceptualization, execution, presentation and contribution to physical therapy practice.

The authors were recognized and awarded a plaque at the Neurology Section’s Business Meeting in Boston, Mass. The article related commentary and podcasts (in the authors own voice) can found at neuropt.org.