Systematic Review

Study Paradigms and Principles Investigated in Motor Learning Research After Stroke: A Scoping Review

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Abstract

Objectives: To (1) characterize study paradigms used to investigate motor learning (ML) poststroke and (2) summarize the effects of different ML principles in promoting skill acquisition and retention. Our secondary objective is to evaluate the clinical utility of ML principles on stroke rehabilitation.

Data Sources: Medline, Excerpta Medica Database, Allied and Complementary Medicine, Cumulative Index to Nursing and Allied Health Literature, and Cochrane Central Register of Controlled Trials were searched from inception on October 24, 2018 and repeated on June 23, 2020. Scopus was searched on January 24, 2019 and July 22, 2020 to identify additional studies.

Study Selection: Our search included keywords and concepts to represent stroke and “motor learning. An iterative process was used to generate study selection criteria. Three authors independently completed title, abstract, and full-text screening.

Data Extraction: Three reviewers independently completed data extraction.

Data Synthesis: The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension guidelines for scoping reviews were used to guide our synthesis. Thirty-nine studies were included. Study designs were heterogeneous, including variability in tasks practiced, acquisition parameters, and retention intervals. ML principles investigated included practice complexity, feedback, motor imagery, mental practice, action observation, implicit and explicit information, aerobic exercise, and neurostimulation. An additional 2 patient-related factors that influence ML were included: stroke characteristics and sleep. Practice complexity, feedback, and mental
One of the most debilitating deficits poststroke is motor impairment.\(^1\),\(^2\) To address this, rehabilitation therapists help individuals practice movements, enabling them to relearn functions affected by their stroke.\(^3\),\(^4\) It is important for the individual’s recovery and function that this “relearning” leads to a permanent change in motor behavior. For example, clinicians may facilitate a better sit-to-stand during therapy, yet the ultimate goal is for the person to stand up independently in their daily life. This rehabilitation process exemplifies motor learning (ML) that is defined as a group of internal processes associated with practice that leads to a relatively permanent change in the capacity for skilled movement.\(^5\) ML is a proposed model for stroke rehabilitation.\(^6\)

Since 2010, a surge of randomized controlled trials has evaluated the effectiveness of different interventions for stroke recovery,\(^7\) leading to best practice guidelines recommending the use of specific therapies (eg, virtual reality, task-specific practice) to improve motor recovery.\(^8\) Although there is strong support for these interventions,\(^6\) it remains unclear if there are optimal conditions in which they can be implemented to maximize effectiveness. Consideration of not only the type of therapy but also the conditions under which the therapy is delivered has the potential to improve motor recovery poststroke. These conditions can be referred to as ML principles.

We define ML principles as conditions during task practice that influence learning and can be applied by rehabilitation clinicians; they are not targeted for a specific movement or therapeutic approach/intervention. As principles of ML can affect learning, they should be used to guide the implementation of neurorehabilitation to promote long-term recovery. The influence of these principles on learning can be scientifically evaluated using ML paradigms. ML paradigms typically have 3 distinct phases: acquisition session(s) when individuals practice a motor skill, retention session(s) where motor skill performance is evaluated after a period of no practice, and transfer testing whereby one tests whether improvements in the practiced skill translates to another similar skill or the same skill under different conditions. Conditions of acquisition sessions (ie, ML principles) influence the trajectory, magnitude, and permanence of learning (assessed by retention testing)\(^9\),\(^10\) and have physiological effects through neuroplasticity and neural recovery.\(^10\) Furthermore, ML principles that promote motor acquisition (eg, blocked practice) may be different than features that are beneficial for motor retention (eg, random practice).\(^9\),\(^11\)

The methods used to investigate ML can affect the interpretation of study results which in turn influences clinical application. However, knowledge about the methods or paradigms used to investigate ML in stroke is limited. A detailed understanding of ML study protocols is necessary to inform stroke rehabilitation. In addition, although previous papers have summarized ML findings poststroke,\(^4\),\(^12\),\(^13\) and Maier et al\(^14\) have recently published a conceptual analysis demonstrating how some ML principles may influence neurorehabilitation efforts, there has been no systematic or comprehensive synthesis of the ML literature involving persons poststroke. For clinicians to be able to use the evidence to inform their practice, they need to be able to easily identify and compare all factors that can influence learning. Therefore, the primary objectives of our study are to (1) summarize and describe the approaches and methods used to investigate ML poststroke and (2) summarize the effects of different ML principles in promoting skill acquisition and retention in individuals’ poststroke. To facilitate the translation of ML research into clinical practice, our secondary objective was to evaluate the clinical utility\(^15\) of each ML principle for stroke rehabilitation.

**Methods**

The methodology for this review is based on the recommendations of Levac et al\(^16\) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension guidelines for scoping reviews.\(^17\) Three authors (S.G., T.S., L.C.) performed article screening, data extraction, quality assessment, and determined ease of clinical application. Discrepancies were resolved through discussion, and a fourth author (K.P.) was consulted if needed.

**Data sources**

We searched 5 databases for studies investigating ML in individuals poststroke on October 24, 2018 and again on June 23, 2020 from inception: Medline (1946 to present), Excerpta Medica Database (1947 to June 22, 2020), Allied and Complementary Medicine (1985 to June 2020), Cumulative Index to Nursing and Allied Health Literature (1981 to present), and the Cochrane Central Register of Controlled Trials (2014 to present). Keywords and Medical Subjects Headings terms for the concepts of “stroke” and “motor learning” were searched using the AND operator, with human and English filters applied. The initial search strategy was created for Medline (table 1) in collaboration with an information specialist and translated for the other
tables. A second information specialist evaluated the initial and translated searches and made suggestions to improve precision and sensitivity.18

Study selection

Early versions of our selection criteria were trialed on a small sample of articles. Variability in study methods and definitions of ML necessitated 10 iterations to refine the selection criteria. Studies were included if they met the final inclusion criteria: (1) individuals poststroke older than 18 years; (2) investigated a ML principle; (3) investigated the learning of a clearly defined motor task; (4) measured motor task performance using the same practice conditions at multiple points throughout acquisition; (5) had a retention interval longer than the interval between each acquisition block (if 1 acquisition session) or each session (if multiple acquisition sessions); (6) the learned motor task was performed and measured at retention under different conditions from the acquisition session (eg, removal of feedback); and (7) the study was written in English. Studies were excluded if (1) the motor task practiced was related to communication, swallowing, eye movements, or perception (attention or sensation) or they were a (2) conference proceeding, review article, thesis, commentary, or protocol. No predefined set of ML principles were used to ensure the review captured the full breadth of the literature.

Tities and abstracts were screened initially, followed by full-text screen of the included abstracts. Full-text exclusion reasons were documented.

The studies cited in the included articles were searched in Scopus (January 24, 2019 and July 22, 2020). All new studies identified were screened with the process outlined above.

Data extraction

A data extraction template was created in Excel (version 16.26) and piloted on 9 studies. Remaining studies were divided between reviewers; 1 extracted the data and the second reviewed the extraction for accuracy. Corresponding authors of included studies were contacted to clarify or gather ambiguous or missing data (3 instances).

The following data were extracted from each study: (1) study demographics: inclusion and exclusion criteria, sample size, age, sex, paretic side, stage of recovery19; (2) ML paradigm: motor task practiced, acquisition conditions, dose of practice, retentional interval, and differences between acquisition and retention testing. We also evaluated if authors explicitly stated that the purpose of their study was to evaluate ML; and (3) ML principle: what was investigated (eg, feedback) and manipulated (eg, frequency of feedback). The ML principle was considered the independent variable for each study.

Ease of clinical application

ML principles were rated on the ease of application in a clinical setting considering the equipment and technology employed in the studies, and whether these were easily accessible in clinical environments with limited financial resources and/or personnel. This scale was used to determine
potential clinical utility and implementation of each ML principle. Separate ratings were given for (1) the ability to duplicate study paradigms in clinical settings and (2) the ease of applying the general principle of ML in clinical practice. Possible ratings were easy, moderate, and hard, and were determined through discussion with members of the research team, all of whom have clinical research experience.

Study quality

Risk of bias was assessed with the appropriate National Institutes of Health National Heart, Lung and Blood Institute quality assessment tool based on study methodology.\(^\text{20}\) One reviewer assessed study quality and a second reviewer checked for assessment accuracy and fit of the tool used.

Results

Selection of sources of evidence

In total, 7043 studies were identified through our database searches. After screening, 39 articles met our inclusion criteria (fig 1).

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Fig 1  Search strategy and results based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews flow diagram.
Study demographics
The 39 included studies were published between 1999 and 2020. Participant demographics are in table 2. Sample sizes of people with stroke ranged from 4 to 91. Thirty-one studies (79%) included individuals with chronic stroke, 21-48,57-59 and 19 studies (50%) enrolled participants starting in the early subacute phase.55,56 One-third of studies (n=13)21,23,26,27,30-34,36,40,41,43-46,48-50,53,57 included a healthy control group. Studies commonly excluded participants with cognitive impairments (n=31, 79%),21-27,28,30-34,36,38,40,41,43-46,48-50,52 or severe motor deficits (n=19, 49%).21,24,30,31,34-37,39,40,44,50,56,59

Methods and approaches used to investigate ML in people poststroke
Despite all included studies using a ML paradigm, only 64% stated that the purpose of their study was to investigate motor (skill) learning (n=19, 49%)22-27,33,37-40,44-48,51,54,57,58 or learning of a motor task (n=6, 15%).21,30,36,43,45,46 Details about the ML paradigms used are summarized in table 3.

Motor task
Motor tasks practiced were broadly separated into upper-extremity (n=28, 72%) and lower-extremity (n=10, 26%) tasks. Seventeen upper-extremity studies included tasks whereby individuals moved to match a visually cued sequence.23-25,28,29,32,33,35,37-40,42,43,46,48,50,52,58 In 5 of these studies, participants moved along a predefined path,26,27,33,38,60 in 2 studies participants reached to a target,32,49 in 2 studies participants completed bimanual cuing tasks,40,51 in 1 study participants practiced spooning food,54 and in 1 study participants practiced a pinching task.40 Of the 10 lower-extremity studies, 4 included balance tasks (weight shifting,29,30,45,46,48,50,52,59 symmetry of limb loading,22,45 2 investigated time to completion of functional movement,21,52 5 included spatiotemporal measures of stepping or walking,37,39,55,56,59 and 2 evaluated the accuracy of weight shifting toward targets in standing.21,36

Measurement of motor task performance
Of the 28 upper-extremity studies, 9 quantified task performance by movement and/or reaction time,24,25,30,41,44,46,48,51,54 9 measured the accuracy and/or error of movement,23,28,29,32,34,35,40,43,53 and 9 used a combination of both to investigate the speed-accuracy trade-off.26-27,33,38,47,49,50,57,59 with 5 of these studies combining speed/accuracy values to create a single score.26-27,33,36,58 One upper-extremity study compared the force and coordination between limbs.42 In the 11 studies that examined learning a lower-extremity motor task, 2 investigated the symmetry of limb loading,22,45 2 examined time to completion of functional movement,21,52 5 included spatiotemporal measures of stepping or walking,37,39,55,56,59 and 2 evaluated the accuracy of weight shifting toward targets in standing.21,36

Structure of acquisition
Dose of practice was reported by describing the number of trials/repetitions (n=23, 59%; range, 1-152), the time for each trial (n=9, 23%; range, 30s-6min), or duration of an acquisition session (n =7, 18%; range, 15min-1h). Most studies (n=25, 64%)22-26,28-30,32-34,36,38,40,41,43,44,46-48,50,53,54,57,58 had multiple practice blocks increasing the total dose of practice. Just over half of the studies (n=21, 54%)22,23,26-27,28,30,32,33,35,37-40,42,43,46,49,51,53,56,58 had a single acquisition session, with 1 study having 56 sessions.55 Breaks were quantified as times between trials/repetitions (n=5, 13%; range, 10s-2 min),34,50,52,53,55 intervals between blocks (n=16, 41%, range, 30s-1h),23,26-27,29,33,34,37,39,41,44,49,51,57-59, or time between sessions (n=2, 5%; range, 1-3d).21,24 Four studies (10%) outlined the presence of a rest period, without defining the duration or timing.29,39,45,56 Finally, within motor imagery, mental practice, or action observation studies (n=5),31,32,45,51,52 4 compared the amount of imagery/observation to physical practice.30,31,51,52 Two studies had equal amounts of physical and observation/imagery practice (ie, 1:1 ratio),30,51 1 study included 5 imagery trials for every physical practice,35 and 1 study had no physical practice trials (imagery only).31

Retention interval
The interval between the final acquisition session and the retention session of the included studies ranged from 10 minutes52 to 1 year.59 The most common retention interval was 1 day (n=16; 41%).25,28,30,32,37,39-41,43,44,46-48,51,53,57 Two studies (5%) had variable retention intervals of 45 minutes to 2 hours or 1-3 days.49 Seven studies (18%) included multiple retention intervals.16-29,34,50,56

Principles influencing ML in stroke
Studies that manipulated similar ML principles were grouped to determine trends across studies. During the screening and subsequent data extraction, 2 additional patient-related factors emerged that did not strictly fit the definition of ML principles, however, were determined to influence ML. These factors could not necessarily be manipulated by the therapist but should be considered when delivering rehabilitation to improve ML. Details describing how ML was analyzed for each study with results are in supplemental table S1 (available online only at http://www.archives-pmr.org/). Summary details about the influence of ML principles on motor acquisition and retention with clinical utility ratings are in table 4.

Patient-related factors
Stroke characteristics. Stroke characteristics evaluated were stroke severity and location. Different clinical outcome measures (ie, the Orpington Prognostic Scale59 and the Fugl-Meyer)60 were used to evaluate stroke severity. Two studies46,49 showed that stroke severity relates to the magnitude of ML and influenced which features of task performance improved. Right versus left hemispheric strokes were compared in 1 study34; stroke location did not significantly affect ML. Motor severity and lesion location were evaluated as principles easy to consider when implementing ML in clinical settings.

Sleep. Two studies investigated the effect of sleep on motor performance. One study found that a full night of sleep
| First Author | Year | Study Country | Groups (n) | Mean Age ± SD, y | Sex, M/F | Stage of Recovery* | Paretic Side, L/R |
|--------------|------|---------------|------------|------------------|----------|-------------------|-----------------|
| Backhaus     | 2018 | Switzerland   | Short nap (10) | 60.0±12.1        | 7/3      | Chronic           | 6/4             |
|              |      |               | Long nap (10)  | 66.3±5.5         | 9/1      |                   | 4/6             |
|              |      |               | No nap (10)    | 59.7±5.5         | 5/5      |                   | 4/6             |
| Bonni        | 2020 | Italy         | Stroke (8)     | 54.1±11.5        | 6/2      | Chronic           | 5/3             |
| Bonuzzi      | 2016 | Brazil        | Stroke (20)    | 65.2±9.3         | 12/8     | Chronic           | 10/10           |
| Bonuzzi      | 2020 | Brazil        | R hemisphere (10) | 62.8±9.8     | 7/3      | Chronic           | 10/0            |
|              |      |               | L hemisphere (10) | 67.5±8.8     | 5/5      |                   | 0/10            |
| Boyd         | 2003 | USA           | Explicit info (5) | 59.0±10.5     | 2/3      | Chronic           | 3/2             |
| Boyd         | 2004 | USA           | No explicit info (5) | 58.6±19.2   | 4/1      | Chronic           | 1/4             |
| Boyd         | 2006 | USA           | BG explicit info (5) | 51.0±9.8    | 4/1      | Chronic           | 4/1             |
|              |      |               | SM explicit info (5) | 59.0±10.5   | 2/3      |                   | 3/2             |
|              |      |               | BG no explicit info (5) | 58.2±14.6   | 3/2      |                   | 4/1             |
|              |      |               | SM no explicit info (5) | 58.6±19.2   | 4/1      |                   | 1/4             |
| Brodie       | 2014 | Canada        | Active rTMS (10) | 64.5±NR       | 8/2      | Chronic           | NR              |
| Brodie       | 2014 | Canada        | Sham rTMS (5)  | 67.2±NR        | 3/2      |                   | NR              |
| Carey        | 2007 | USA           | Track (10)     | 65.9±7.4        | 9/1      | Chronic           | 5/5             |
| Charalambous | 2018 | USA           | Treadmill walking (12) | 55.1±16.0  | 7/5      | Chronic           | 7/5             |
|              |      |               | Cycle ergometer (12) | 62.2±10.1   | 7/5      |                   | 8/4             |
|              |      |               | Active control (13) | 57.5±9.0    | 9/4      |                   | 6/7             |
| Cirstea      | 2003 | Canada        | Mild−moderate (10) | 54.4±20.1    | 5/5      | Late subacute−chronic | 0/10           |
|              |      |               | Moderate−severe (10) | 52.5±11.6   | 8/2      |                   | 0/10            |
| Dobkin       | 2010 | 11 countries  | Daily reinforcement (88) | 62.9±12.6   | 59%/41%  | Early subacute    | 49%/51%         |
| Doost        | 2019 | Belgium       | Stroke (21)    | 65.1±8.0        | 16/5     | Chronic           | 12/9            |
| Guttmann     | 2012 | Israel        | Stroke (13)    | 68.9±4.9        | 10/3     | Chronic           | 5/8             |
| Hamoudi      | 2018 | Germany       | Real tDCS (18) | 61.6±3         | 12/6     | Late subacute−chronic | 10/8           |
|              |      |               | Sham tDCS (18) | 61.9±3         | 15/3     |                   | 9/9             |
|              |      |               | No training/tDCS (14) | 64.7±2      | 8/6      |                   | 7/7             |
| Helm         | 2020 | USA           | Variable (16)  | 58.7±11.3       | 12/4     | Chronic           | NR              |
|              |      |               | Constant (16)  | 62.3±9.7       | 7/9      |                   | NR              |
| Jo           | 2020 | Korea         | Random (7)     | 57.7±7.4        | 5/2      | Late subacute−chronic | 0/7             |
| Lefebvre     | 2013 | Belgium       | Stroke (18)    | 61±9            | 12/6     | Chronic           | 10/8            |
| Lefebvre     | 2015 | Belgium       | Stroke (19)    | 65±10           | 16/3     | Chronic           | 5/14            |
| Lefebvre     | 2017 | Belgium       | Stroke (22)    | 64.7±9.8       | 18/4     | Chronic           | NR              |
| Malouin      | 2009 | Canada        | Mental practice (5) | 61.3±7.2    | 3/2      | Chronic           | 5/0             |
|              |      |               | Cognitive practice (3) | 61.0±8.5   | 3/0      |                   | 2/1             |
|              |      |               | No training (4) | 61.8±9.5      | 4/0      |                   | 3/1             |
| Nepveu       | 2017 | Canada        | HIIT (11)      | 64.7±11.6      | 6/5      | Chronic           | 1/10            |
| Neva         | 2019 | Canada        | No exercise (11) | 65.0±11.3    | 10/1     |                   | 3/7/1           |
|              |      |               | M1 cTBS (12)   | 62.3±9.7      | 9/3      | Chronic           | 6/6             |
|              |      |               | S1 cTBS (13)   | 66.5±13.0     | 11/2     |                   | 6/7             |
|              |      |               | Sham cTBS (12) | 68.2±9.1      | 9/3      |                   | 5/7             |
| First Author | Year | Study Country | Groups (n) | Mean Age ± SD, y | Sex, M/F | Stage of Recovery | Paretic Side, L/R |
|--------------|------|---------------|------------|------------------|----------|------------------|------------------|
| Orrell²²     | 2006 | UK            | Discovery learning (5) | 49.20±15.71   | 4/1      | Chronic          | 2/2/1**          |
|              |      |               | Errorless learning (5) | 54.60±12.16   | 5/0      |                  |                  |
| Ploughman⁵⁶  | 2018 | Canada        | Stroke (10) | 58.2±14.9      | 4/6      | Early subacute–chronic | 2/8              |
|              |      |               |            | 71±6           | 29/18    | Chronic          | NR               |
| Pollock⁵⁹    | 2014 | Canada        | Stroke (4) | 61.75±6.75     | 4/0      | Chronic          | 3/1              |
| Quattrocchi³²| 2017 | UK            | Reward (15) | 58.9±3.1       | 10/5     | Chronic          | 8/7              |
|              |      |               | Punishment (15) | 56.3±3.4      | 7/8      |                  |                  |
|              |      |               | Neutral (15) | 58.5±3.6      | 9/6      |                  |                  |
|              |      |               | Added imagery (12) | 59.7±13.0   | 7/5      |                  |                  |
|              |      |               | No imagery (14) | 64.4±6.8     | 10/4     |                  |                  |
| Schuster⁵²   | 2012 | UK and Switzerland | Embedded imagery (13) | 65.8±10.2     | 10/3     | Late subacute–chronic | 4/9              |
|              |      |               |          | 59.7±3.1       | 4/6      |pattern         | 6/6.              |
|              |      |               |          | 71±6           | 29/18    | Chronic          | NR               |
|              |      |               |          | 58.5±3.6       | 9/6      |                  |                  |
| Schweighofer⁵³| 2011 | USA           | Blocked (12) | 61.25±13.92   | 8/4      | Late subacute–chronic | 6/6.              |
|              |      |               | Random (13) | 54.58±13.39   | 9/4      |                  |                  |
| Siengsukon²³ | 2009 | USA/Canada    | Explicit info—sleep (10) | 62.2±10.3     | 6/4      | Chronic          | 6/4              |
|              |      |               | Explicit info—no sleep (10) | 59.8±13.7     | 5/5      |                  | 3/7              |
|              |      |               | Implicit info—sleep (10) | 62.9±10.5     | 6/4      |                  | 7/3              |
|              |      |               | Implicit info—no sleep (10) | 65.4±15.4     | 3/7      |                  | 7/3              |
|              |      |               |          | 64.4±6.8       | 10/4     |                  |                  |
|              |      |               |          | 59.7±3.1       | 4/6      |pattern         | 6/6.              |
|              |      |               |          | 59.7±13.0      | 7/5      |pattern         |                  |
|              |      |               |          | 64.4±6.8       | 10/4     |pattern         |                  |
|              |      |               |          | 65.4±15.4      | 3/7      |pattern         |                  |
|              |      |               |          | 61.25±13.92    | 8/4      |pattern         |                  |
| Schorre⁵²    | 2012 | Japan         | rTMS unaffected (9) | 60.4±5.8      | 6/3      | Chronic          | 6/3              |
|              |      |               | Combined rTMS and tDCS (9) | 57.0±10.2    | 6/3      |                  | 3/6              |
| Tretriluxana⁵¹| 2014 | Thailand      | Dyad (10)  | 50-70 ¹       | NR       | Late subacute–chronic | NR               |
|              |      |               | Individual (10) | 50-70 ¹     | NR       |                  |                  |
| Tretriluxana³⁰| 2015 | Thailand      | 6-min observation (6) | 60.67±2.81    | NR       | Chronic          | NR               |
|              |      |               | 1-min observation (6) | 64.83±7.52   | NR       |                  |                  |
| Vliet³³      | 2017 | Netherlands   | Short-lasting online (20) | 64±11        | 15/5     | Chronic          | 11/9             |
|              |      |               | Long-lasting offline (18) | 60±8        | 8/13     |                  | 9/12             |
|              |      |               | Short-lasting offline (21) | 62±11       | 14/7     |                  | 11/10            |
| Wadden⁶⁴     | 2019 | Canada        | M1 cTBS (9) | 60.2±10.3     | 21/7 ¹¹  | Chronic          | NR               |
|              |      |               | S1 cTBS (11) | 67.2±16.1    | 21/7 ¹¹  |                  |                  |
|              |      |               | Sham cTBS (8) | 68.5±11.2    | 21/7 ¹¹  |                  |                  |
| Winsten⁴³    | 1999 | USA           | Stroke (40) ¹ | 57.1±11.1    | 26/14    | Chronic          | 20/20            |
| Zimerman²⁸  | 2012 | Germany       | Stroke (12) | 58.3±11.1     | 6/6      | Chronic          | 7/5              |

NOTE. Only groups that matched the inclusion criteria are reported in this table. Abbreviations: BG, basal ganglia; F, female; HIIT, high-intensity interval training; L, left; M, male; NR, not reported; R, right; SM, sensorimotor; tDCS, transcranial direct current stimulation; UK, United Kingdom; USA, United States of America.

* Time poststroke is classified based on the following categories: acute (<1wk), early subacute (1wk-3mo), late subacute (3-6mo), and chronic (>6mo).

† Crossover study with all participants information grouped together.

‡ Study contained other groups not reported.

§ Classified based on initial grouping.

∥ Separated by Fugl-Meyer score: mild-moderate group range=63-50, moderate-severe group range=46-5.

¶ Demographics of all stroke groups reported together.

⁎ Bilateral lesions.

** Cerebellum lesion.

†† Reported as a range.
| First Author | Year | Motor Task | Motor Task Performance Measure | Structure of Acquisition | Retention Interval |
|--------------|------|------------|--------------------------------|--------------------------|-------------------|
| Backhaus34   | 2018 | Visuomotor adaptation task (joystick to targets with 110° rotation) | Accuracy (targets hit) | • Length of trial: 150 s<sup>*</sup>  
• No. of trials/sessions: 6  
• No. of sessions: 1 | 45 min-2 h; 1 d |
| Bonni35      | 2020 | Visuomotor adaptation task (joystick to target with 30° rotation) | Movement (angular) error | • No. of trials/blocks: 152  
• No. of blocks: 1  
• No. of sessions: 1 | 45 min |
| Brodie24     | 2014 | STT (move cursor between targets) | Response time; peak velocity; cumulative distance | • No. of trials/blocks: 72  
• No. of blocks: 6  
• No. of sessions: 6 | 1-3 d |
| Brodie25     | 2014 | STT (move cursor between targets) | Responses time (reaction and movement time combined) | • No. of trials/blocks: 72  
• No. of blocks: 6  
• No. of sessions: 5 | 1 d |
| Boyd48       | 2003 | SRTT (press key corresponding to cued target) | Response time (with related change score) | • No. of trials/blocks: 10  
• No. of blocks/sessions: 5  
• No. of sessions: 3 | 1 d |
| Boyd57       | 2004 | CTT (matching rotation of lever to cued pattern) | Tracking error; lag time; tracking accuracy | • No. of trials/blocks: 10  
• No. of blocks/sessions: 5  
• No. of sessions: 3 | 1 d |
| Boyd47       | 2006 | SRTT (press key corresponding to cued target); CTT (matching rotation of lever to cued pattern) | SRTT—response time; CTT—tracking error  
To compare tasks—change score | • No. of trials/blocks: 10  
• No. of blocks/sessions: 5  
• No. of sessions: 3 | 1 d |
| Carey29      | 2007 | Matching finger and wrist potion to cued pattern | Accuracy score | • No. of reps/blocks: 3  
• No. of blocks/sessions: 60  
• No. of sessions: 10 | 3 mo |
| Cirstea49    | 2003 | Reaching to target | Movement precision; movement time; movement segmentation; kinematics | • No. of trials/sessions: 70  
• No. of sessions: 1 | 10 min |
| Doost38      | 2019 | Bimanual circuit game (move cursor along complex path) | Bimanual speed-accuracy trade-off, bimanual coordination | • Length of trial: 30 s  
• No. of trials/sessions: 30  
• No. of sessions: 1 | 1 wk |
| Hamoudi50    | 2018 | Matching pinch force to cued pattern | Speed; accuracy (error rate) | • No. of reps/blocks: 20  
• No. of blocks: 5  
• No. of sessions: 5 | 3, 24, 52, 80, and 108 d |
| Jo54         | 2020 | Spooning task | Movement time | • No. of trials/blocks: 15  
• No. of blocks: 3  
• No. of sessions: 9 | 3 wk |

(continued)
| First Author | Year | Motor Task                                      | Motor Task Performance Measure                                                                 | Structure of Acquisition                                                                                   | Retention Interval |
|--------------|------|-----------------------------------------------|--------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|--------------------|
| Lefebvre     | 2013 | Circuit game (move cursor along complex path) | Learning index (based on velocity and error)                                                   * Length of trial: 30 s * No. of trials/sessions: 30 * No. of sessions: 1                         | 30 min, 11 60 min, 1 wk                                                                                   |                    |
| Lefebvre     | 2015 | Circuit game (move cursor along complex path) | Learning index (based on velocity and error)                                                   * Length of trial: 30 s * No. of trials/sessions: 30 * No. of sessions: 1                         | 1 wk                                                                                                      |                    |
| Lefebvre     | 2017 | Circuit game (move cursor along complex path) | Learning index (based on velocity and error)                                                   * Length of trial: 30 s * No. of trials/sessions: 30 * No. of sessions: 1                         | 30 min, 1 h, 1 wk                                                                                         |                    |
| Nepveu       | 2017 | Handgrip task (match grip force to target)    | Accuracy (time on target)                                                                     * No. of trials/blocks: 20 * No. of blocks: 5 * No. of sessions: 1                                           | 1 d                                                                                                       |                    |
| Neva         | 2019 | STT (move cursor between targets)             | Total response time (reaction and movement time combined)                                       * No. of trials/blocks: 111 * No. of blocks: 4 * No. of sessions: 5                                      | 1 d                                                                                                       |                    |
| Pohl         | 2001 | Matching closing different switches to cued patterns | Sequence response time                                                                     * No. of trials/blocks: 10 * No. of blocks: 8 * No. of sessions: 1                                           | 1 d                                                                                                       |                    |
| Quattrocchi  | 2017 | Planar reaching to target with a force field perturbation | Difference between target angle and angular hand position (ie, angular error) at peak outward velocity | * No. of trials/blocks: 50 * No. of blocks/sessions: 7 * No. of sessions: 1                               | 1 d                                                                                                       |                    |
| Schweighofer | 2011 | Matching grip force to cued pattern            | Normalized error of force trajectory                                                           * No. of trials/blocks: 50 OR 3 * No. of blocks/sessions: 3 or 50 * No. of sessions: 1       | 1 d                                                                                                       |                    |
| Siengsukon   | 2009 | CTT (matching joystick position to cued pattern) | Tracking accuracy                                                                             * No. of trials/blocks: 10 * No. of blocks: 10 * No. of sessions: 1                                           | 12 h                                                          |                    |
| Takeuchi     | 2012 | Pinching task                                 | Pinch force; bimanual coordination                                                              * Length of session: 15 min * No. of sessions: 1                                                        | 1 wk                                                                                                       |                    |
| Tretriluxana | 2014 | Bimanual cup stacking                         | Movement time; reaction time                                                                   * No. of trials/blocks: 5 * No. of blocks/sessions: 4 * Observation-practice ratio: 1:1 (if applicable) * No. of sessions: 1 | 1 d                                                                                                       |                    |

(continued)
| First Author | Year | Motor Task | Motor Task Performance Measure | Structure of Acquisition | Retention Interval |
|--------------|------|------------|--------------------------------|--------------------------|-------------------|
| Tretriluxana 30 | 2015 | Bimanual cup stacking | Movement time; reaction time | • No. (length) of trials: 4 (6min) or 24 (1min)  
• Length of block: 6 min  
• Observation-practice ratio: 1:1  
• No. of sessions: 1 | 1 d |
| Vliet 23 | 2017 | Circuit game (move cursor along complex path) | Motor skill change (based on speed and errors) | • No. of trials/blocks: 5  
• No. of blocks/sessions: 9  
• No. of sessions: 1 | 1 wk |
| Wadden 64 | 2019 | STT (move cursor between targets) | Total response time (reaction and movement time combined) | • No. of trials/blocks: 102  
• No. of blocks: 4  
• No. of sessions: 5 | 1 d |
| Weinstein 43 | 1999 | Matching planar elbow flexion/extension movements to cued pattern | Average difference between movement pattern and cued pattern; variable error (consistency) | • No. of trials/blocks: 99  
• No. of blocks/sessions: 2  
• No. of sessions: 1 | 1 d |
| Zimerman 58 | 2012 | SRTT (press key corresponding to cued target) | No. of correct sequences | • Length per trial: 3 min  
• No. of trials/sessions: 5  
• No. of sessions: 1 | 90 min, 1 d, 3 mo |
| Lower-extremity motor tasks | | | | | |
| Bonuzzi 21 | 2016 | Weight shifting to targets in standing | Complexity of game; no. of errors; no. of correct weight shifts | • Length of session: 30 min  
• No. of sessions: 4 | 1 wk |
| Bonuzzi 36 | 2020 | Weight shifting to targets in standing | Complexity of game; no. of errors; no. of correct weight shifts | • Length of trial: 10 min  
• No. of trials/sessions: 3  
• No. of sessions: 4 | 1 wk |
| Charalambous 37 | 2018 | Gait (split-belt treadmill) | Step length symmetry index | • Length of session: 15 min  
• No. of sessions: 1 | 1 d |
| Dobkin 55 | 2010 | Walking as quickly as possible | Gait speed | • No. of trials/sessions: 1  
• No. of sessions: daily to 8 wk | 3, 6 mo |
| Helm 39 | 2020 | Gait (split-belt treadmill) | Step length symmetry, limb phase symmetry | • Length sessions: 15 min  
• No. of sessions: 1 | 1 d |
| Malouin 45 | 2009 | Sit to stand | Loading of paretic leg (% of body weight) | • Length of session: 1 h  
• Imagery-practice ratio: CD  
• No. of sessions: 12 | 3 wk |

(continued)
| First Author | Year | Motor Task | Motor Task Performance Measure | Structure of Acquisition | Retention Interval |
|--------------|------|------------|-------------------------------|--------------------------|-------------------|
| Orrell       | 2006 | Symmetry of standing; ability to keep board standing on stable | Degree the board tilts from horizontal | Length of trial: 60 s  No. of trials/session: 24  No. of sessions: 1 | 15 min, 1 wk |
| Ploughman    | 2018 | Gait       | Cadence, velocity, % in double support, step length symmetry | No. of trials: 4 passes  No. of sessions: 1 | 5, 20 min |
| Pollock      | 2014 | Reactive stepping in response to leaning outside base of support | Step velocity; step length | No. of trials/blocks: 60  No. of blocks/sessions: 2  No. of sessions: 12 | 1 y |
| Schuster     | 2012 | Lie down on floor and then stand up | Speed | Length of session: 45-50 min  Imagery-practice ratio: 5:1  No. of sessions: 6 | 2 wk |
| Upper- and lower-extremity motor tasks | | | | | |
| Guttman      | 2012 | Sit to stand, reach to grasp | Time to stand; maximum reaching velocity | Length of session: 15 min (imagery)  No. of sessions: 12 | 4 wk |

Abbreviations: CD, cannot determine; CTT, continuous tracking task; SRTT, serial reaction time task; STT, serial targeting task.
* Includes a block with random rotations.
† Includes both random and repeated sequences."One group only physical practiced during the first 2 sessions.
‡ Data for this retention interval not reported.
§ Based on if groups are in randomized or blocked practice.
¶ Practice embedded into PT session.
# Repetitions varied per individual.
| First Author, Year | ML Principle Category | ML Manipulation Details | Effect on Acquisition | Effect on Retention | Simplified Conclusion | Ease of Implementation* |
|--------------------|-----------------------|------------------------|----------------------|---------------------|-----------------------|-------------------------|
| Bonuzzi, 2020      | Stroke location       | Hemisphere damaged     | +/1                  | +/1                 | Side of stroke lesion does not affect ML. | ML: easy; Paradigm: moderate |
| Cirstea, 2003      | Stroke severity       | Severity of motor impairment | +/1                  | +/1                 | Stroke severity influences the aspect of motor performance that changes. | ML: easy; Paradigm: easy |
| Pohl, 2001         | Stroke severity       | Severity of motor impairment | +/1                  | +/1                 | Greater motor performance improvements with mild vs moderate stroke. | ML: easy; Paradigm: hard |
| Bonuzzi, 2016      | Task complexity and structure of practice | Task complexity increased during acquisition | +/1                  | +/1                 | Increasing task difficulty is effective in promoting motor improvements poststroke. | ML: easy; Paradigm: moderate |
| Helm, 2020         | Task complexity and structure of practice | Practice structure (constant vs variable practice) | +/1                  | +/1                 | Both constant and variable practice can promote motor adaptation improvements. | ML: easy; Paradigm: hard |
| Jo, 2020           | Task complexity and structure of practice | Practice structure (blocked vs random practice) | -/1                  | -/1                 | There was no difference in blocked or random practice on motor acquisition or retention. | ML: easy; Paradigm: easy |
| Orrell, 2006       | Task complexity and structure of practice | Errorless vs discovery learning | CD                  | +/1                 | Both errorless and discovery learning can promote motor performance improvements. | ML: easy; Paradigm: easy |
| Pollock, 2014      | Task complexity and structure of practice | Task complexity increased during acquisition | +/1                  | +/1                 | Increasing task difficulty is effective in promoting motor improvements poststroke. | ML: easy; Paradigm: Moderate |
| Schweighofer, 2011 | Task complexity and structure of practice | Practice structure (blocked vs random practice) | +/1                  | +/1                 | Random practice structure is more effective than blocked practice in promoting motor improvements that are maintained overtime. | ML: easy; Paradigm: hard |
| Carey, 2007         | Feedback              | Feedback through telerehabilitation | +/1                  | +/1                 | Providing feedback is effective in promoting motor improvements poststroke. | ML: easy; Paradigm: moderate |
| Dobkin, 2010       | Feedback              | Daily feedback vs no feedback | +/1                  | +/1                 | Providing daily feedback is effective in promoting motor improvements poststroke. | ML: easy; Paradigm: easy |
| Ploughman, 2018    | Feedback              | Mode of feedback (tactile vs verbal) | +/1                  | +/1                 | More features of movement are improved with tactile compared to verbal feedback; however, improvements are not maintained long term. | ML: easy; Paradigm: easy |
| Quattrocchi, 2017  | Feedback              | Content of feedback (reward, punishment, neutral) | +/1                  | +/1                 | Positive and negative feedback is more effective at promoting motor improvement than neutral feedback. | ML: easy; Paradigm: hard |
| Winstein, 1999     | Feedback              | Frequency of feedback (100% vs 67%) | +/1                  | +/1                 | Feedback helps promote ML; however, the frequency of feedback did not make a significant difference. | ML: easy; Paradigm: hard |
| Guttman, 2012      | Motor imagery, mental practice, and action observation | Mental imagery without physical practice | +/1                  | +/1                 | Mental imagery without physical practice is effective in promoting motor improvements poststroke. | ML: easy; Paradigm: easy |

(continued)
| First Author, Year | ML Principle Category | ML Manipulation Details | Effect on Acquisition | Effect on Retention | Simplified Conclusion | Ease of Implementation* |
|--------------------|----------------------|------------------------|----------------------|---------------------|----------------------|------------------------|
| Malouin, 2009       | Motor imagery, mental | Mental practice vs cognitive | +1                   | +                   | Mental practice is more effective in promoting motor improvements than practicing unrelated cognitive tasks. | ML: easy | Paradigm: easy |
|                    | practice, and action  | practice vs control    |                      |                     |                      |                        |                        |
|                    | observation           |                        |                      |                     |                      |                        |                        |
| Schuster, 2012      | Motor imagery, mental | Timing of mental imagery | +1                   | +1                  | The timing of mental imagery has no influence on ML. | ML: easy | Paradigm: easy |
|                    | practice, and action  | (embedded vs consecutive, vs control) |                      |                     |                      |                        |                        |
|                    | observation           |                        |                      |                     |                      |                        |                        |
| Tretriluxana, 2014  | Motor imagery, mental | Action observation with physical | +1                   | +1, -1              | Action observation is effective in promoting improvements in movement time, but not reaction time poststroke. | ML: easy | Paradigm: easy |
|                    | practice, and action  | practice, vs physical practice alone |                      |                     |                      |                        |                        |
|                    | observation           |                        |                      |                     |                      |                        |                        |
| Tretriluxana, 2015  | Motor imagery, mental | Duration of action observation (6 vs 1min) | +1                   | +1                  | Longer duration of observation is most effective in promoting motor improvements poststroke | ML: easy | Paradigm: easy |
|                    | practice, and action  |                        |                      |                     |                      |                        |                        |
| Boyd, 2003          | Implicit vs Explicit  | Explicit information vs no explicit information | +1                   | NR                  | Provision of explicit information about the task is detrimental to ML poststroke. | ML: easy | Paradigm: moderate |
|                    | Information           |                        |                      |                     |                      |                        |                        |
| Boyd, 2004          | Implicit vs explicit  | Explicit information vs no explicit information | +1                   | +1                  | Provision of explicit information about the task is detrimental to ML poststroke. | ML: easy | Paradigm: moderate |
|                    | information           |                        |                      |                     |                      |                        |                        |
| Boyd, 2006          | Implicit vs explicit  | Explicit information vs no explicit information, comparing lesion location | +1                   | +1                  | Regardless of lesion location or type of task, provision of explicit information about the task is detrimental to ML poststroke. | ML: easy | Paradigm: moderate |
|                    | information           |                        |                      |                     |                      |                        |                        |
| Charalambous, 2018  | Aerobic exercise      | Treadmill vs cycle ergometer vs active control | +1                   | +1                  | Neither intensity nor timing of exercise (as a primer) improves ML poststroke. | ML: moderate | Paradigm: moderate |
| Nepveu, 2017        | Aerobic exercise      | Exercise vs no exercise | +1                   | +1                  | High-intensity interval training after motor training improves motor retention. | ML: moderate | Paradigm: hard |
| Backhaus, 2018      | Sleep                 | Short vs long term napping, vs no napping | +1                   | +                  | Napping does not enhance long-term retention poststroke. | ML: easy | Paradigm: moderate |
| Siengsukon, 2000    | Sleep                 | Sleep vs no sleep      | +1                   | +                  | Sleep promotes the maintenance of motor improvements. | ML: easy | Paradigm: moderate |
| Bonni, 2020         | Neurostimulation      | Active vs sham ITBS over lateral cerebellum, prior to task practice | +1                   | NR                  | ITBS prior over the lateral cerebellum prior to training improves ML poststroke. | ML: hard | Paradigm: hard |
| Brodie, 2014        | Neurostimulation      | Active vs sham rTMS over ipsilesional-S1, prior to task practice | +1                   | +, -1               | Active rTMS over the ipsilesional-S1 prior to training improves ML poststroke. | ML: hard | Paradigm: hard |
| Brodie, 2014        | Neurostimulation      | Active vs sham rTMS over ipsilesional-S1, prior to task practice | +1                   | +, -1               | Active rTMS over the ipsilesional-S1 prior to training improves ML poststroke. | ML: hard | Paradigm: hard |
| Doost, 2019         | Neurostimulation      | Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition | +1                   | +                  | Active dual-tDCS does not enhance ML compared to sham stimulation. | ML: hard | Paradigm: hard |
| Hamoudi, 2018       | Neurostimulation      | Active vs sham TDCS over ipsilesional-M1, mid acquisition | +1                   | +                  | Active tDCS over the ipsilesional-M1 during training improves acquisition of motor skills poststroke. | ML: hard | Paradigm: hard |
| Lefebvre, 2013      | Neurostimulation      | Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition | +1                   | +                  | Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke | ML: hard | Paradigm: hard |
| First Author, Year | ML Principle Category | ML Manipulation Details | Effect on Acquisition | Effect on Retention | Simplified Conclusion | Ease of Implementation* |
|-------------------|----------------------|-------------------------|----------------------|---------------------|-----------------------|-------------------------|
| Lefebvre, 2015    | Neurostimulation     | Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition | +1                   | +1                  | Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke. | ML: hard Paradigm: hard |
| Lefebvre, 2017    | Neurostimulation     | Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition | +1, +1               | +1                  | Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke | ML: hard Paradigm: hard |
| Neva, 2019        | Neurostimulation     | Contralesional M1 vs S1 vs sham cTBS, prior to practice | NR                   | +1                  | cTBS does not enhance motor acquisition or retention, regardless of the location of stimulation. | ML: hard Paradigm: hard |
| Takeuchi, 2012    | Neurostimulation     | rTMS over contralesional vs tDCS over ipsilesional vs combined rTMS-tDCS | +1/-1                | +1/-1               | Combination of rTMS-tDCS may help promote ML more than a single type of stimulation. | ML: hard Paradigm: hard |
| Vliet, 2017       | Neurostimulation     | Active vs sham tDCS over ipsilesional-M1, within various durations and timing | +1                   | +1                  | The amount or timing of bihemispheric tDCS does not influence the amount ML. | ML: hard Paradigm: hard |
| Wadden, 2019      | Neurostimulation     | Contralesional M1 vs S1 vs sham cTBS, prior to practice | +1, +1               | NR                  | cTBS does not enhance motor acquisition or retention, regardless of the location of stimulation | ML: hard Paradigm: hard |
| Zimerman, 2012    | Neurostimulation     | Active vs sham cathodal tDCS over contralesional-M1 during learning | +1                   | +1, +1              | Active cathodal tDCS over contralesional-M1 during training improves acquisition and shorter-term (up to 1d) retention but not long-term (3mo) retention of motor tasks. | ML: hard Paradigm: hard |

NOTE. + is improvement in motor performance during acquisition, maintenance in motor improvements at retention; – is no motor improvement noted during acquisition, loss of improvement at retention.

Abbreviations: CD, cannot determine; NR, not reported.

* For the ease of implementation, “ML” is the ease of applying the general principle of ML in clinical practice; and “paradigm” is the ease of duplicating the study paradigm in clinical settings.

† Significant ML group differences.

‡ Based-on reviewers’ observation of figure.
between acquisition and retention sessions enhanced motor retention of both implicitly and explicitly cued tasks. In contrast, the second study found that daytime napping does not enhance ML. Sleep was rated easy to monitor in a clinical setting.

**ML paradigm conditions**

**Practice complexity.** Two studies investigated the effects of increasing task complexity throughout the practice trials and found that this facilitated ML. One study evaluated if learning without error (less complex) was more effective than learning through error (more complex), but there was no significant difference in motor performance at retention. Practice complexity was manipulated using constant/ blocked versus variable/random practice in 3 studies. Random/variable practice promoted maintenance of motor improvements in 1 study, but was not significantly different from constant/block practice in 2 studies. Study paradigms for practice complexity varied in rating for reproducibility; overall, however, it was determined to be easy to implement clinically.

**Feedback.** Feedback was investigated in 5 studies. Two studies compared feedback to a no-feedback control; both studies found feedback facilitated ML. Furthermore, the mode (tactile vs verbal), frequency (100% vs 67%), and content (reward and punishment) of feedback influenced motor acquisition, but had smaller and less consistent effects on retention. ML paradigms varied in difficulty to duplicate; yet, it was consistently rated that it would be easy to manipulate how feedback is provided in clinical settings.

**Motor imagery/mental practice and action observation.** Five studies with components outside of typical physical practice—motor imagery, mental practice, and action observation—were grouped together. These principles were rated as easy to implement clinically and were all found to have a positive effect on ML. All studies had participants imagine/observe functional motor tasks. Improvements in motor performance were found irrespective of timing of mental imagery, or if physical practice was performed. One study found that longer sessions of observation and practice promoted greater motor improvements during retention testing.

**Implicit and explicit information.** Three studies compared the effects of explicit versus implicit cues. All studies showed a negative effect of providing explicit information (ie, description of movement sequences to be learned) on ML. The task paradigm in these studies required technology that resulted in a rating of moderate difficulty to duplicate; however, providing implicit over explicit cues was rated easily implementable clinically.

**Aerobic exercise.** Two studies evaluated the effect of aerobic exercise either before or after motor task practice on ML with conflicting results. One study investigating a locomotor learning task found no effect of exercise on ML whereas another study using a hand grasp-force task found that high-intensity interval training enhanced retention performance. Raters determined that it is moderately difficult to apply high-intensity aerobic exercise enhance ML in clinical practice.

**Neurostimulation.** Thirteen studies investigated the effect of different types of neurostimulation on ML including transcranial direct current stimulation (tDCS), repetitive transcranial magnetic stimulation (rTMS), continuous theta burst stimulation (cTBS), and intermittent theta burst stimulation (iTBS). Seven studies investigated the effect of 1mA active tDCS compared to sham stimulation during task practice. Montages included dual or bihemispheric stimulation with the anode over ipsilesional-M1, a single site of anodal stimulation over ipsilesional-M1, or a single site of cathodal stimulation over contralesional-M1. Most studies found a positive effect of tDCS on acquisition and, at minimum, active stimulation helped improve short-term retention of motor skills. However, 2 studies showed no significant group differences between active and sham stimulation groups. Two studies, which included the same participants, investigated the influence of 5Hz rTMS over ipsilesional-S1 prior to task practice. rTMS promoted acquisition and retention of motor skills to a greater extent than sham stimulation. One study compared rTMS to tDCS, to the combination of both prior to practice, and found that rTMS-only initially decreased motor performance after stimulation. However, groups that contained rTMS maintained motor improvements better at retention. Two studies investigated the use of cTBS over S1 versus M1 stimulation prior to practice, neither enhanced ML greater than sham stimulation. Finally, iTBS over the cerebellum was found to enhance motor acquisition and retention greater than sham stimulation. Based on the technology, personnel, and training required it was rated hard to implement neurostimulation in clinical settings.

**Study quality**

Study quality evaluation ratings are in table 5. Nineteen studies were evaluated using the tool for controlled interventions; 9 studies received a rating of good, and 10 studies received a rating of fair. Nine studies that were assessed used the pre-post study with no control intervention tool; 7 had a good rating, and 2 had a fair rating. Finally, 11 studies were assessed using the tool for observational cohort and cross-sectional studies; 5 studies were rated good, and 6 studies were rated fair.

**Discussion**

This scoping review found fair to good quality evidence regarding the influence of ML principles on the acquisition and retention of motor skills poststroke. Overall, we found variability in how ML paradigms were implemented in stroke research. Key ML principles and patient-related factors with consistent evidence of influence on ML were stroke severity, practice complexity, feedback, mental practice, action observation, implicit and explicit information. These principles, in addition to sleep, and practice schedule, were all
| First Author, Year | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 | Q14 | Overall Rating |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----------------|
| Backhaus, 2018    | Y  | Y  | Y  | NA | NA | Y  | N  | N  | N  | Y  | Y  | Y  | N  | Y  | Y  | Fair          |
| Bonni, 2020       | Y  | N  | N  | Y  | N  | Y  | Y  | Y  | Y  | N  | Y  | N  | Y  | Y  | Fair          |
| Bonuzzi, 2020     | N  | NA | NA | NA | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Fair       |
| Brodie, 2014      | Y  | Y  | NR | NA | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Good        |
| Brodie, 2014      | Y  | Y  | NR | NA | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Good        |
| Charalambos, 2018 | N  | NR | NA | NA | NA | Y  | NR | NR | Y  | Y  | N  | Y  | Y  | Fair        |
| Dobkin, 2010      | Y  | Y  | NR | Y  | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Fair        |
| Dood, 2019        | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Good        |
| Hamoudi, 2018     | Y  | Y  | NR | NR | NA | Y  | Y  | Y  | Y  | NR | Y  | Y  | Y  | Good        |
| Helm, 2020        | Y  | NR | NR | N  | N  | Y  | N  | Y  | N  | Y  | Y  | Y  | Y  | Fair        |
| Jo, 2020          | Y  | N  | N  | N  | N  | Y  | Y  | Y  | Y  | N  | Y  | N  | Y  | Fair        |
| Malouin, 2009     | Y  | Y  | NR | NR | Y  | NR | NR | Y  | Y  | Y  | N  | Y  | Y  | Fair        |
| Nepveu, 2017      | Y  | NR | NA | NA | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Good        |
| Neva, 2019        | N  | Y  | N  | Y  | Y  | Y  | Y  | Y  | NR | Y  | N  | Y  | Y  | Good        |
| Schuster, 2012    | Y  | Y  | Y  | N  | N  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Fair        |
| Stengelkus, 2009  | Y  | N  | NR | NA | NA | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | Fair        |
| Takeuchi, 2012    | Y  | NR | NR | NA | NA | Y  | NR | NR | Y  | Y  | NR | Y  | Y  | Fair        |
| Vilest, 2017      | Y  | Y  | CD | Y  | Y  | N  | Y  | Y  | Y  | NR | Y  | Y  | Y  | Good        |
| Wadden, 2019      | Y  | Y  | Y  | NA | NA | Y  | NR | NR | Y  | Y  | Y  | Y  | Y  | Good        |

| First Author, Year | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 | Q14 | Overall Rating |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----------------|
| Bonuzzi, 2016     | Y  | Y  | Y  | Y  | Y  | N  | Y  | Y  | NR | Y  | Y  | Y  | CD | NA | Good          |
| Gutzman, 2021     | Y  | y  | y  | N  | Y  | y  | N  | N  | Y  | Y  | Y  | Y  | Y  | NA | Good          |
| Lefebvre, 2013    | Y  | y  | y  | NR | Y  | y  | N  | N  | Y  | Y  | Y  | Y  | Y  | NA | Good          |
| Lefebvre, 2015    | Y  | y  | y  | CD | Y  | y  | N  | N  | Y  | Y  | Y  | Y  | Y  | NA | Fair          |
| Lefebvre, 2019    | Y  | N  | Y  | N  | y  | Y  | y  | N  | N  | Y  | Y  | Y  | Y  | NA | Good          |
| Ploughman, 2018   | Y  | Y  | Y  | Y  | Y  | y  | Y  | Y  | y  | Y  | Y  | Y  | Y  | NA | Good          |
| Pohl, 2001        | Y  | Y  | N  | Y  | y  | Y  | Y  | Y  | N  | Y  | Y  | Y  | N  | Good        |
| Pollock, 2014     | Y  | Y  | N  | NR | N  | y  | Y  | N  | Y  | NR | N  | N  | N  | NA | Fair          |
| Zinnerman, 2012   | Y  | N  | Y  | NR | CD | Y  | Y  | Y  | Y  | Y  | Y  | Y  | Y  | NA | Good          |
Motor learning after stroke: a scoping review

Variable methods and paradigms used to investigate ML poststroke

Most of the ML studies (n=31, 79%) were conducted with people with chronic stroke. This may limit clinical application because the subacute stage is when inpatient rehabilitation primarily occurs and where potential for neuroplasticity is highest. The type and measurement of motor tasks varied across studies. Most studies (n=28, 74%) evaluated ML in the upper extremity with novel tasks, which may reduce the ecological validity for rehabilitation poststroke. In contrast, lower-extremity (n=10, 26%) tasks were functional including walking, balance, and transitional movements. It is possible that ML is different for common lower-extremity tasks compared to novel upper-extremity tasks because task experience (i.e., novice vs expert) influences learning in neurotypical populations. Because ML groupings consisted of both upper- and lower-extremity studies to meet study objectives, task differences may limit the comparability of studies. One study that evaluated ML in the upper- and lower-extremity showed that individuals improved motor performance for both tasks. However, both tasks were functional movements (reach-to-grasp and sit-to-stand) and the authors did not compare the magnitude or trajectory of learning between tasks.

Measurement of motor performance also differed between upper- and lower-extremity studies. Speed and/or accuracy measures were often used for upper-extremity tasks, whereas lower-extremity measurements were more variable. Studies assessing multiple components of motor performance found that movement accuracy and timing improved at the detriment of optimal kinematics. This phenomenon has also been observed in gait; although people with stroke can increase their gait velocity, they do so with a more atypical gait pattern. Thus, how motor performance is measured influences whether a change will be considered a positive ML outcome. The definition of motor improvement should be considered carefully when interpreting study findings, especially when applied clinically.

Magnitude of motor improvement exhibited by individuals with and without neurologic conditions is tightly linked to the amount of practice, thus it should be considered when interpreting study results. Structure and reported dose of practice during acquisition varied greatly across the included studies. Most studies (n=23, 59%) reported the exact number of task repetitions, with additional information about the distribution of repetitions within sessions. However, some studies only provided the duration of a practice session, meaning the exact number of movements executed likely varied between participants. Previous work has shown that age, side affected, time poststroke, and stroke severity cannot be used to understand the varying amount of practice within a physiotherapy session. It is therefore...
challenging to determine how the dose of practice in the included studies affected our results. Finally, most of the studies had a single acquisition practice session. This was more common among upper-extremity studies \((n=18\) of 28) than lower-extremity studies \((n=4\) of 10). Considering the dose-response relation, it is unsurprising that many studies found only modest improvements in motor performance.

Clinicians aim to facilitate motor improvement during therapy that has lasting effect on a client’s everyday function after rehabilitation is complete. Therefore, research that aims to investigate ML principles to be applied in stroke rehabilitation practice must include retention sessions. This is because retention testing enables researchers and clinicians to draw conclusions about ML (ie, relatively permanent changes in motor behavior) and distinguish it from motor performance which refers to temporary fluctuations in behavior that can be observed and measured during or immediately after the acquisition session.64 However, of the studies that reached full-text screening stage, 168 of 306 \((55\%)\) were excluded from our review for not meeting retention criterion. This included not having retention testing, or not having a change of practice condition at retention testing as recommended for ML studies.65 Within these excluded studies, additional ML principles (eg, focus of attention) were investigated in persons with stroke. However, the clinical implications of these findings for ML and stroke recovery were unclear because of a lack of retention testing. It is essential that future ML studies in stroke include retention testing to ensure conclusions about ML can be drawn to facilitate clinical application of the results. It is also important to consider the retention interval when evaluating permanence of motor improvement, as motor performance can decay as retention intervals increase.66 Of the included studies, 51% \((n=20)\) had a retention interval of 1 day or shorter. Furthermore, of the 6 studies that showed improvements in task performance during acquisition, and had a retention interval of 3 weeks or longer,28,29,31,45,50,55 4 studies maintained improvements over the retention period40,45,50,55 and 2 studies showed a decline in task performance or a loss of any group differences during retention.28,31 Therefore, longer retention intervals or multiple retention sessions may provide meaningful information related to short- versus long-term recovery of motor skills poststroke.

**Influence of ML principles on skill acquisition and retention and their clinical application**

The large variability in ML paradigms made meta-analysis infeasible and complicated comparisons of study findings. However, we used qualitative summaries of trends across studies and clinical utility and implementation ratings to investigate how ML principles might be incorporated into clinical practice.

**Patient-related factors**

**Stroke characteristics.** The heterogenous clinical presentation of stroke requires clinicians to individualize therapy to maximize outcomes.6 It was unsurprising to learn that stroke presentation also influences ML. Therefore, although clinicians do not manipulate stroke severity, because it is inherent to the client, it is important that stroke characteristics are considered when creating rehabilitation programs. We found that regardless of stroke severity or location, all individuals improved with task-specific practice and therefore should have access to rehabilitation. Although stroke location did not affect ML, stroke severity influenced the magnitude and mechanism of motor improvements.46,49 Individuals with moderate-severe strokes often improved motor performance through compensation (ie, increased trunk flexion during reaching).49 Thus, it is important to be mindful of how motor performance is measured within a study because the measure of task completion or movement quality can influence how clinicians use study results to guide their own practice with patients. Overall, it is recommended to consider the balance between task completion and movement quality in combination with patient goals and stroke characteristics when structuring therapy sessions to facilitate ML and recovery.

Sleep. Sleep, like stroke severity, is not a factor easily manipulated by rehabilitation therapists. However, it is estimated that sleep is impaired in up to 78% of persons with stroke and thus is an important consideration when implementing a rehabilitation program.65 We found conflicting evidence about the effect of sleep on ML.23,34 This conflict may be because study protocol factors (ie, time of testing48 and task features51) that mediate the influence of sleep on learning. However, a small meta-analysis looking at sleep on ML found that overall sleep does enhance ML in persons with stroke or other brain lesions, more so than healthy adults.69 Therefore, despite conflicting results in our study, and considering the relative ease of administering sleep questionnaires, clinicians may wish to evaluate sleep in persons with stroke and monitor the association with the motor outcomes of their interventions.

**ML paradigm conditions**

**Practice complexity.** Our review found benefits to progressing the challenge of a task as people learn59; this likely facilitates neuroadaptation.70 However, it is important to control the amount of challenge because individuals with stroke can perform better in transfer conditions when error is minimized.22 Therefore, clinicians should carefully titrate task difficulty to the individual’s skill level60 to optimize ML; something that is feasible for clinicians to do. One example of a method to monitor task challenge is the NASA Task Load Index (NASA-TLX), a scale that is used to measure the work load efforts of a task on multiple domains including mental demands, physical demands, temporal demands, performance, effort, and frustration.71 ML research with neurotypical adults has found that optimal ML occurs with a NASA-TLX score of 51.5.72 Future research should determine if a NASA-TLX score of 51.5 is optimal to promote ML in the stroke population as well.

Practice complexity can also be manipulated through the structure (ie, variability) of practice. Motor performance during acquisition with random practice is similar to blocked practice,39,53,54 but 1 study exhibited less decay at retention with random practice.23 This is consistent with other ML studies in neurotypical adults73 and people poststroke,74 and is supported by the forgetting-reconstruction hypothesis, whereby each time an individual repeats a task they make stronger memory representations of the task that are easier to recall.51 This provides evidence that clinicians should consider
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how to disperse exercises/movements within a single therapy session. For example, for perturbation based-balance training, clinicians can randomize the direction of their external perturbations, instead of grouping all perturbations by direction, to increase the unpredictability and practice complexity. Together these studies highlight the importance of continuing to progress the difficulty of a task, making sure that the clients find the task challenging but not beyond their skill level, as well as varying task practice to facilitate improved long-term retention and generalization of motor performance.

**Feedback.** It is clear from the 3 controlled studies that augmented feedback significantly improves both motor acquisition and retention poststroke. 29,32,55 These benefits remain even when delivered remotely through telerehabilitation as seen in 1 included study, 29 a promising finding for communities with limited rehabilitation resources. Our review found good quality evidence that certain features of feedback mediates ML responses. Meaningful feedback (rewarding or punishing) is more effective than neutral feedback. 32 In addition, 100% feedback trended to be more effective for motor acquisition and retention compared to faded feedback on 67% of trials, 32 which differs from ML in neurotypical populations. 11 Finally, tactile feedback was associated with better motor acquisition compared to verbal cueing during practice in 1 study; differences were not maintained at retention. 32 This may be a result of the small dose of practice in this study, so definitive conclusions about mode of feedback cannot be drawn at this time. In summary, feedback is beneficial for ML poststroke; however, further investigation is required to understand the optimal mode of delivery, frequency, and content because this information can guide clinician’s provision of feedback to clients.

**Motor imagery/mental practice and action observation.** This review found fair to good quality evidence that motor imagery facilitates motor acquisition even with limited physical task practice. 32,45,52 There were conflicting conclusions about the effect of motor imagery/mental practice on skill retention, 32,45,52 which may be because of differences in acquisition parameters. Motor imagery can be easily applied in a clinical setting and it enables task practice when individuals may be too tired for physical activity or if they want to practice a motor task that is beyond their current capabilities. Improvements are thought to be mediated through similar cortical networks active during imagined compared to physical movement. 76 Therefore, motor imagery/mental practice should be a technique that clinicians consider implementing to help facilitate ML.

This review also found action observation to be beneficial for ML poststroke, which is consistent with results in neurotypical adults. 77 Practice combined with observation was found to be more effective than physical practice alone for equal duration. 51 In addition, longer observation was more effective than multiple shorter observation sessions, 30 which may be because of certain mirror neurons only discharging after repeated observation. 78 These studies provide evidence that individuals may benefit from repeated demonstration of movements to help them achieve motor goals.

**Implicit and explicit information.** Our review found strong evidence that regardless of the location of stroke (ie, basal ganglia or sensorimotor cortex) or type of task practiced (ie, continuous or discrete tasks), explicit provision of the sequence of task to be learned was detrimental to ML. 32,45,52 This is opposite to the facilitatory effect of explicit cues in neurotypical adults. 48 The cognitive load of remembering explicit instructions during task practice (ie, dual-task) may exceed the capacity of individuals with stroke and interfere with ML. An alternative explanation is that explicit information inhibits the creation of implicit memories, especially with more severe strokes. 79 These consistent conclusions suggest that clinicians should be cognizant about how they instruct clients to complete an exercise/movement. As suggested by Boyd et al, 48 this may involve orienting clients focus on components of movement that are atypical (eg, telling a client their knees fully extend too early during sit-to-stand) yet allow them to make their own corrections to improve the sequence of movement without explicit direction.

**Aerobic exercise.** We found preliminary conflicting evidence on the effects of aerobic exercise on ML. One study of good quality found that high-intensity interval training after task practice modestly improved the neuroplastic response by mediating the amount of interhemispheric inhibition, thus enhancing ML. 50 In contrast, the second included exercise study did not find a beneficial effect of high- compared to low-intensity exercise, though this could be a result of all groups showing adaptation to the split-belt treadmill paradigm used. 37 Many studies have shown that aerobic exercise promotes neuroplasticity by increasing the production of brain derived neurotrophic factor in rats, 80 healthy adults, 81 and persons with stroke. 82 Nonetheless, more work is needed to understand the benefits of aerobic exercise for ML before it is widely implemented clinically for ML purposes specifically.

**Neurostimulation.** There was good quality evidence that neurostimulation can enhance ML poststroke using various montages and techniques, before (for rTMS, iTBS) or during (for tDCS) practice. Compared to sham stimulation, cTBS was not found to enhance ML. Despite the benefits, it was consistently determined that neurostimulation is difficult to implement clinically. Future research evaluating how to improve the feasibility of neurostimulation implementation clinically is warranted.

**Study limitations**

Although our study consolidates information related to ML poststroke, there are limitations to this review. We acknowledge that there are ML principles (eg, focus of attention) that were not evaluated owing to a lack of suitable studies available in the stroke literature. In addition, some factors influencing ML were evaluated by a single study (eg, lesioned hemisphere) in this review, limiting the strength of our conclusions regarding clinical effect. Many of the included studies implemented a pre-post study design to investigate ML principles. Although this study design shows the magnitude ML, it fails to provide a full picture about the trajectory of learning. Understanding how people learn (illustrated by ML curves with multiple measures of motor performance
throughout acquisition) in addition to the magnitude of learning can provide clinically useful information about the optimal dose or length of intervention. Finally, many included studies exhibited selection bias by excluding individuals with cognitive impairment or severe motor dysfunction. This limits generalizability of study findings because approximately 85% of people poststroke have cognitive impairment.83,84

Two ways to address some of the limitations in this review are to make the identification of ML studies easier by explicitly stating objectives related to ML, and have future studies be more consistent in implementation and reporting of ML paradigms and principles. Current poststroke ML studies have heterogenous designs, making it challenging to compare study findings. Variability also exists in the outcomes used to evaluate ML. For example, some studies evaluated retention session by comparing motor performance at retention to the baseline performance values (savings), whereas other studies reported differences from retention to end of acquisition training (forgetting). This variability leads to challenges interpreting ML study results, which may explain why many clinicians recognize the importance of ML principles on recovery but do not use them to guide their practice.85 Creating ML reporting guidelines, similar to the Consensus on Exercise Reporting Template used for the reporting of exercise programs,68 may address this issue.

Conclusions

Reporting guidelines for ML studies would be beneficial to enable easier comparison and interpretation of study findings as well as facilitate future meta-analyses to better inform clinical practice. Despite differences between ML study paradigms and clinical rehabilitation practice, the goal of permanent gains in skilled motor performance remains consistent. This review identified consistent evidence that ML poststroke is influenced by stroke severity, task complexity, motor imagery, action observation, and feedback that could be easily implemented in clinical practice. Other ML principles or patient-related factors influencing ML with conflicting evidence on ML effect—ie, sleep, practice schedules, and aerobic exercise—are worth further investigation given they also would be relatively easily applied clinically. This review also identified a considerable amount of research on various types of neurostimulation, yet the resulting effects on ML are varied and clinical implementation will be a challenge. Research on people in the subacute stage of recovery, with severe impairment, or cognitive deficits would be valuable for this research field.

Supplier

a. Excel, version 16.26; Microsoft Corporation.

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