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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

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List of abbreviations: cTBS, continuous theta burst stimulation; iTBS, intermittent theta burst stimulation; ML, motor learning; NASA-TLX, NASA Task Load Index; rTMS, repetitive transcranial magnetic stimulation; tDCS, transcranial direct current stimulation.

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practice/action observation most consistently promoted ML, while provision of explicit information and more severe strokes were detrimental to ML. Other factors (ie, sleep, practice structure, aerobic exercise, neurostimulation) had a less clear influence on learning.

Conclusions: Improved consistency of reporting in ML studies is needed to improve study comparability and facilitate meta-analyses to better understand the influence of ML principles on learning poststroke. Knowledge of ML principles and patient-related factors that influence ML, with clinical judgment can guide neurologic rehabilitation delivery to improve patient motor outcomes.

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,[8] 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)[4,9] 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).[4,11]

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 Nurisng and Allied Health Litrerature (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

Table 1 Search strategy for Medline

No.	Searches	Results (October 24, 2018)	Results (June 23, 2020)
1	Cerebrovascular disorders/	45,411	46,338
2	Stroke rehabilitation/	11,212	13,166
3	Exp stroke/	117,205	122,630
4	(stroke* or poststroke or transient isch* or TIA or cerebrovascular* or CVA).ti,ab,kf.	266,053	11,630
5	((cerebral or cerebellar or brain* or vertebrobasilar or intracerebral) adj5 (infarct$ or isch?emi* or thrombo* or emboli* or apoplexy or occlus*)).ti,ab,kf.	91,346	99,567
6	((cerebral or intracerebral or intracranial or brain* or cerebellar) adj5 (h?emorrhage or h?ematoma* or bleed*)).ti,ab,kf.	44,664	49,589
7	exp hemiplegia/ or exp paresis/	18,552	19,384
8	(hemipleg* or hemipar* or paresis or paretic).ti,ab,kf.	33,874	36,283
9	or/1-8 [**stroke]	411,790	456,028
10	((motor or skill) adj5 (learn* or relearn* or acquisition or reacquisition)).ti,ab,kf.	12,733	14,585
11	((motor or skill) adj5 (retention* or transfer*)).ti,ab,kf.	2008	2292
12	Motor activity/	93,056	96,406
13	Motor skills/	22,652	24,183
14	Psychomotor performance/	59,569	63,629
15	Learning/	59,114	65,169
16	(12 or 13 or 14) and 15	6700	7223
17	10 or 11 or 16 [**motor learning]	18,233	20,573
18	9 and 17	1053	1212
19	18 not (exp animals/ not humans.sh.)	928	1073
20	Limit 19 to English	884	1028
21	(201810* or 201811* or 201812* or 2019* or 2020*).dt.		2,309,454
22	20 and 21		147

databases. 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.

Titles 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)[a] 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 recovery[19]; (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.[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).

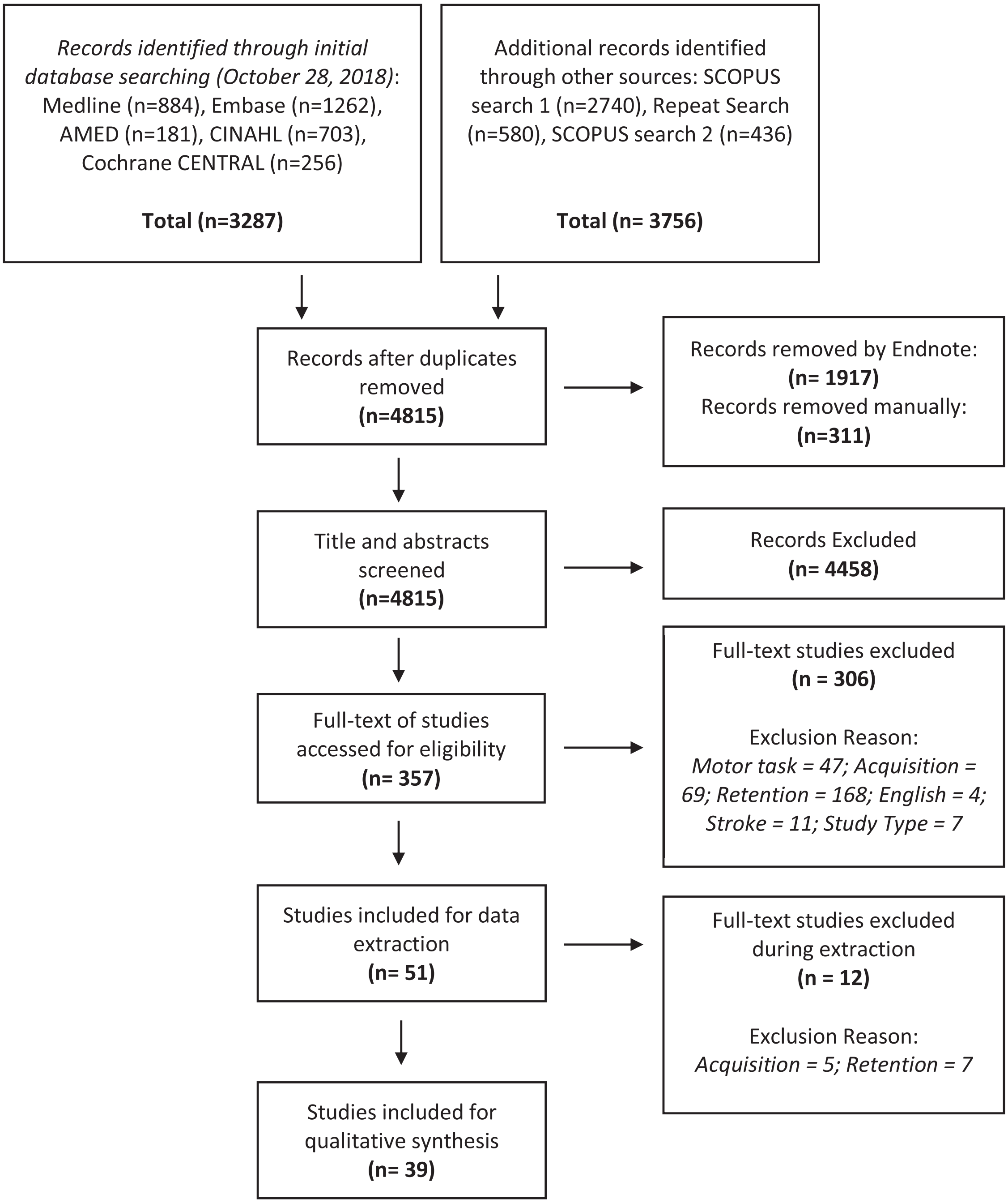

Fig 1 Search strategy and results based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews flow diagram.

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] 6 studies (15%) enrolled individuals at least 3 months poststroke (late subacute),[49-54] and 2 studies (5%) enrolled participants starting in the early subacute phase.[55,56] One-third of studies (n=13)[21-23,32,34,36,43,46,47-49,53,57] 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—58] 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.[23-25,28,29,35,34,40,41,43,44,46,47,48,50,53,57] 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 cup stacking,[30,51] 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,[21,36] symmetry of standing,[22] reactive balance[59]), 4 investigated gait,[37,39,55,56] and 2 examined transitional movements (sit-to-stand,[45] stand-to-lie-to-stand[52]). One study included both upper-extremity (reach-to-grasp) and lower-extremity (sit-to-stand) tasks.[31]

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,[31,52] 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,[52] 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 minutes[49] 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.[24] Seven studies (18%) included multiple retention intervals.[26-29,34,50,56]

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 Scale[46] and the Fugl-Meyer[49]) were used to evaluate stroke severity. Two studies[46,49] 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 study[37]; 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

Table 2 Demographics of participants in the included studies

First Author	Year	Study Country	Groups (n)	Mean Age ± SD, y	Sex, M/F	Stage of Recovery[*]	Paretic Side, L/R
Backhaus[34]	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[35]	2020	Italy	Stroke (8)[†]	54.1±11.5	6/2	Chronic	5/3
Bonuzzi[21]	2016	Brazil	Stroke (20)[‡]	65.2±9.3	12/8	Chronic	10/10
Bonuzzi[36]	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[48]	2003	USA	Explicit info (5)	59.0±10.5	2/3	Chronic	3/2
			No explicit info (5)	58.6±19.2	4/1		1/4
Boyd[57]	2004	USA	Explicit info (5)	51.0±9.8	4/1	Chronic	4/1
			No explicit info (5)	58.2±14.6	3/2		4/1
Boyd[47]	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[24]	2014	Canada	Active rTMS (10)[§]	64.5±NR	8/2	Chronic	NR
			Sham rTMS (5)[§]	67.2±NR	3/2		NR
Brodie[25]	2014	Canada	rTMS (11)	65.1±6.8	9/2	Chronic	5/6
			Sham rTMS (11)	67.4±6.7	8/3		5/6
Carey[29]	2007	USA	Track (10)[‡]	65.9±7.4	9/1	Chronic	5/5
Charalambous[37]	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[49]	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[55]	2010	11 countries	Daily reinforcement (88)	62.9±12.6	59%/41%[¶]	Early subacute	49%/51%[¶]
			No reinforcement (91)	65.1±11.9			
Doost[38]	2019	Belgium	Stroke (21)[†]	65.1±8.0	16/5	Chronic	12/9
Guttman[31]	2012	Israel	Stroke (13)[†]	68.9±4.9	10/3	Chronic	5/8
Hamoudi[50]	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[39]	2020	USA	Variable (16)	58.7±11.3	12/4	Chronic	NR
			Constant (16)	62.3±9.7	7/9		NR
Jo[54]	2020	Korea	Random (7)	57.7±7.4	5/2	Late subacute–chronic	0/7
			Blocked (7)	63.1±8.0	4/3		0/7
Lefebvre[27]	2013	Belgium	Stroke (18)[†]	61±9	12/6	Chronic	10/8
Lefebvre[58]	2015	Belgium	Stroke (19)[†]	65±10	16/3	Chronic	5/14
Lefebvre[26]	2017	Belgium	Stroke (22)[†]	64.7±9.8	18/4	Chronic	NR
Malouin[45]	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[40]	2017	Canada	HIIT (11)	64.7±11.6	6/5	Chronic	1/10
			No exercise (11)	65.0±11.3	10/1		3/7/1[#]
Neva[41]	2019	Canada	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

(continued)

Table 2 (*Continued*)

First Author	Year	Study Country	Groups (n)	Mean Age ± SD, y	Sex, M/F	Stage of Recovery[*]	Paretic Side, L/R
Orrell[22]	2006	UK	Discovery learning (5)	49.20±15.71	4/1	Chronic	2/2/1[**]
			Errorless learning (5)	54.60±12.16	5/0		3/1/1[#]
Ploughman[56]	2018	Canada	Stroke (10)[†]	58.2±14.9	4/6	Early subacute–chronic	2/8
Pohl[46]	2001	USA	Stroke (47)	71±6	29/18	Chronic	NR
Pollock[59]	2014	Canada	Stroke (4)	61.75±6.75	4/0	Chronic	3/1
Quattrocchi[32]	2017	UK	Reward (15)	58.9±3.1	10/5	Chronic	8/7
			Punishment (15)	56. 3±3.4	7/8		9/6
			Neutral (15)	58.5±3.6	9/6		9/6
Schuster[52]	2012	UK and Switzerland	Embedded imagery (13)	65. 8±10.2	10/3	Late subacute–chronic	4/9
			Added imagery (12)	59.7±13.0	7/5		5/7
			No imagery (14)	64.4±6.8	10/4		8/6
Schweighofer[53]	2011	USA	Blocked (12)	61.25±13.92	8/4	Late subacute–chronic	6/6
			Random (13)	54.58±13.39	9/4		4/9
Siengsukon[23]	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
Takeuchi[42]	2012	Japan	rTMS unaffected (9)	64.0±5.8	6/3	Chronic	6/3
			tDCS affected (9)	63.4±6.7	5/4		5/4
			Combined rTMS and tDCS (9)	57.0±10.2	6/3		3/6
Tretriluxana[51]	2014	Thailand	Dyad (10)	50-70[††]	NR	Late subacute–chronic	NR
			Individual (10)	50-70[††]			
Tretriluxana[30]	2015	Thailand	6-min observation (6)	60.67±2.81	NR	Chronic	NR
			1-min observation (6)	64.83±7.52			
Vliet[33]	2017	Netherlands	Short-lasting online (20)	64±11	15/5	Chronic	11/9
			Long-lasting offline (18)	59±9	12/6		11/7
			Short-lasting offline (21)	60±8	8/13		9/12
			Sham (21)	62±11	14/7		11/10
Wadden[44]	2019	Canada	M1 cTBS (9)	60.2±10.3	21/7[‖]	Chronic	NR
			S1 cTBS (11)	67.2±16.1			
			Sham cTBS (8)	68.5±11.2			
Winstein[43]	1999	USA	Stroke (40)[¶]	57.1±11.1	26/14	Chronic	20/20
Zimerman[28]	2012	Germany	Stroke (12)[†]	58.3±NR	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 classifed based on the following categoreies: 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.

Table 3 Motor learning paradigms

First Author	Year	Motor Task	Motor Task Performance Measure	Structure of Acquisition	Retention Interval
Upper-extremity motor tasks					
Backhaus[34]	2018	Visuomotor adaptation task (joystick to targets with 110° rotation)	Accuracy (targets hit)	• Length of trial: 150 s* • No. of trials/sessions: 6 • No. of sessions: 1	45 min-2 h; 1 d
Bonni[35]	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
Brodie[24]	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
Brodie[25]	2014	STT (move cursor between targets)	Reponses time (reaction and movement time combined)	• No. of trials/blocks: 72† • No. of blocks: 6 • No. of sessions: 5	1 d
Boyd[48]	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
Boyd[57]	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
Boyd[47]	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
Carey[29]	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
Cirstea[49]	2003	Reaching to target	Movement precision; movement time; movement segmentation; kinematics	• No. of trials/sessions: 70 • No. of sessions: 1	10 min
Doost[38]	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
Hamoudi[50]	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
Jo[54]	2020	Spooning task	Movement time	• No. of trials/blocks: 15 • No. of blocks: 3 • No. of sessions: 9	3 wk

(*continued*)

Table 3 (*Continued*)

First Author	Year	Motor Task	Motor Task Performance Measure	Structure of Acquisition	Retention Interval
Lefebvre[27]	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,[‖] 60 min, 1 wk
Lefebvre[58]	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[26]	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[40]	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[41]	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[46]	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[32]	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[53]	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[23]	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[42]	2012	Pinching task	Pinch force; bimanual coordination	• Length of session: 15 min • No. of sessions: 1	1 wk
Tretriluxana[51]	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*)

Table 3 (*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[33]	2017	Circuit game (move cursor along complex path)	Motor skill change (based on speed and errors)	• No. of trials/bocks: 5 • No. of blocks/sessions: 9 • No. of sessions: 1	1 wk
Wadden[44]	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
Winstein[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/bocks: 99 • No. of blocks/sessions: 2 • No. of sessions: 1	1 d
Zimerman[28]	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*)

Table 3 (*Continued*)

First Author	Year	Motor Task	Motor Task Performance Measure	Structure of Acquisition	Retention Interval
Orrell[22]	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[56]	2018	Gait	Cadence, velocity, % in double support, step length symmetry	• No. of trials: 4 passes • No. of sessions: 1	5, 20 min
Pollock[59]	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[52]	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[31]	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.

Table 4 Summary table on the effect of ML principles on acquisition and retention of motor skills poststroke

First Author, Year	ML Principle Category	ML Manipulation Details	Effect on Acquisition	Effect on Retention	Simplified Conclusion	Ease of Implementation[*]
Bonuzzi, 2020[35]	Stroke location	Hemisphere damaged	+[†]	+[†]	Side of stroke lesion does not affect ML.	ML: easy Paradigm: moderate
Cirstea, 2003[49]	Stroke severity	Severity of motor impairment	+[†]	+	Stroke severity influences the aspect of motor performance that changes.	ML: easy Paradigm: easy
Pohl, 2001[46]	Stroke severity	Severity of motor impairment	+[‡]	+[‡,§]	Greater motor performance improvements with mild vs moderate stroke.	ML: easy Paradigm: hard
Bonuzzi, 2016[21]	Task complexity and structure of practice	Task complexity increased during acquisition	+[§]	+[§]	Increasing task difficulty is effective in promoting motor improvements poststroke.	ML: easy Paradigm: moderate
Helm, 2020[39]	Task complexity and structure of practice	Practice structure (constant vs variable practice)	+[†]	+[†]	Both constant and variable practice can promote motor adaptation improvements.	ML: easy Paradigm: hard
Jo, 2020[54]	Task complexity and structure of practice	Practice structure (blocked vs random practice)	—[†]	—[†]	There was no difference in blocked or random practice on motor acquisition or retention.	ML: easy Paradigm: easy
Orrell, 2006[22]	Task complexity and structure of practice	Errorless vs discovery learning	CD	+[†]	Both errorless and discovery learning can promote motor performance improvements.	ML: easy Paradigm: easy
Pollock, 2014[59]	Task complexity and structure of practice	Task complexity increased during acquisition	+	+/—	Increasing task difficulty is effective in promoting motor improvements poststroke.	ML: easy Paradigm: Moderate
Schweighofer, 2011[53]	Task complexity and structure of practice	Practice structure (blocked vs random practice)	+[†]	+[‡]	Random practice structure is more effective than blocked practice in promoting motor improvements that are maintained overtime.	ML: easy Paradigm: hard
Carey, 2007[29]	Feedback	Feedback through telerehabilitation	+	+	Providing feedback is effective in promoting motor improvements poststroke.	ML: easy Paradigm: moderate
Dobkin, 2010[55]	Feedback	Daily feedback vs no feedback	+[‡]	+[‡]	Providing daily feedback is effective in promoting motor improvements poststroke.	ML: easy Paradigm: easy
Ploughman, 2018[56]	Feedback	Mode of feedback (tactile vs verbal)	+[‡/†]	—	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[32]	Feedback	Content of feedback (reward, punishment, neutral)	+[†]	+[†]	Positive and negative feedback is more effective at promoting motor improvement than neutral feedback.	ML: easy Paradigm: hard
Winstein, 1999[43]	Feedback	Frequency of feedback (100% vs 67%)	+[†]	—	Feedback helps promote ML; however, the frequency of feedback did not make a significant difference.	ML: easy Paradigm: hard
Guttman, 2012[31]	Motor imagery, mental practice, and action observation	Mental imagery without physical practice	+	+/—	Mental imagery without physical practice is effective in promoting motor improvements poststroke.	ML: easy Paradigm: easy

(*continued*)

Table 4 (*Continued*)

First Author, Year	ML Principle Category	ML Manipulation Details	Effect on Acquisition	Effect on Retention	Simplified Conclusion	Ease of Implementation[*]
Malouin, 2009[45]	Motor imagery, mental practice, and action observation	Mental practice vs cognitive practice vs control	+[‡]	+	Mental practice is more effective in promoting motor improvements than practicing unrelated cognitive tasks.	ML: easy Paradigm: easy
Schuster, 2012[52]	Motor imagery, mental practice, and action observation	Timing of mental imagery (embedded vs consecutive, vs control)	+[†]	+[†]	The timing of mental imagery has no influence on ML.	ML: easy Paradigm: easy
Tretriluxana, 2014[54]	Motor imagery, mental practice, and action observation	Action observation with physical practice, vs physical practice alone	+[†,‡]	+[†,‡]	Action observation is effective in promoting improvements in movement time, but not reaction time poststroke.	ML: easy Paradigm: easy
Tretriluxana, 2015[30]	Motor imagery, mental practice, and action observation	Duration of action observation (6 vs 1min)	+[†]	+[‡]	Longer duration of observation is most effective in promoting motor improvements poststroke	ML: easy Paradigm: easy
Boyd, 2003[48]	Implicit vs Explicit Information	Explicit information vs no explicit information	+[‡]	NR[‡]	Provision of explicit information about the task is detrimental to ML poststroke.	ML: easy Paradigm: moderate
Boyd, 2004[57]	Implicit vs explicit information	Explicit information vs no explicit information	+[†,‡]	+[†,‡]	Provision of explicit information about the task is detrimental to ML poststroke.	ML: easy Paradigm: moderate
Boyd, 2006[47]	Implicit vs explicit information	Explicit information vs no explicit information, comparing lesion location	+[‡]	+[‡,§]	Regardless of lesion location or type of task, provision of explicit information about the task is detrimental to ML poststroke.	ML: easy Paradigm: moderate
Charalambous, 2018[37]	Aerobic exercise	Treadmill vs cycle ergometer vs active control	+[†]	+[†]	Neither intensity nor timing of exercise (as a primer) improves ML poststroke.	ML: moderate Paradigm: moderate
Nepveu, 2017[40]	Aerobic exercise	Exercise vs no exercise	+[†]	+/—[‡]	High-intensity interval training after motor training improves motor retention.	ML: moderate Paradigm: hard
Backhaus, 2018[34]	Sleep	Short vs long term napping, vs no napping	+[†]	+/—[†]	Napping does not enhance long-term retention poststroke.	ML: easy Paradigm: moderate
Siengsukon, 2009[23]	Sleep	Sleep vs no sleep	+[CD]	+[‡]	Sleep promotes the maintenance of motor improvements.	ML: easy Paradigm: moderate
Bonni, 2020[35]	Neurostimulation	Active vs sham iTBS over lateral cerebellum, prior to task practice	+[‡]	NR[‡]	iTBS prior over the lateral cerebellum prior to training improves ML poststroke.	ML: hard Paradigm: hard
Brodie, 2014[24]	Neurostimulation	Active vs sham rTMS over ipsilesional-S1, prior to task practice	+[‡]	+[†,‡]	Active rTMS over the ipsilesional-S1 prior to training improves ML poststroke.	ML: hard Paradigm: hard
Brodie, 2014[25]	Neurostimulation	Active vs sham rTMS over ipsilesional-S1, prior to task practice	+[‡]	+[†,‡]	Active rTMS over the ipsilesional-S1 prior to training improves ML poststroke.	ML: hard Paradigm: hard
Doost, 2019[38]	Neurostimulation	Active vs sham dual-tDCS over ipsilesional-M1, midacquisition	+[†]	+[†]	Active dual-tDCS does not enhance ML compared to sham stimulation.	ML: hard Paradigm: hard
Hamoudi, 2018[50]	Neurostimulation	Active vs sham tDCS over ipsilesional-M1, mid acquisition	+[‡]	+[†]	Active tDCS over the ipsilesional-M1 during training improves acquisition of motor skills poststroke.	ML: hard Paradigm: hard
Lefebvre, 2013[27]	Neurostimulation	Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition	+[‡]	+[‡]	Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke	ML: hard Paradigm: hard

(*continued*)

Table 4 (*Continued*)

First Author, Year	ML Principle Category	ML Manipulation Details	Effect on Acquisition	Effect on Retention	Simplified Conclusion	Ease of Implementation[*]
Lefebvre, 2015[58]	Neurostimulation	Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition	+[‡]	+[‡]	Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke.	ML: hard Paradigm: hard
Lefebvre, 2017[26]	Neurostimulation	Active vs sham dual-tDCS over ipsilesional-M1, mid acquisition	+[‡,§]	+[‡]	Active tDCS over the ipsilesional-M1 during training improves acquisition and retention of motor skills poststroke	ML: hard Paradigm: hard
Neva, 2019[41]	Neurostimulation	Contralesional M1 vs S1 vs sham cTBS, prior to practice	NR[†]	+[†]	cTBS does not enhance motor acquisition or retention, regardless of the location of stimulation.	ML: hard Paradigm: hard
Takeuchi, 2012[42]	Neurostimulation	rTMS over contralesional vs tDCS over ipsilesional vs combined rTMS-tDCS	+/—[‡]	+/—[‡]	Combination of rTMS-tDCS may help promote ML more than a single type of stimulation.	ML: hard Paradigm: hard
Vliet, 2017[33]	Neurostimulation	Active vs sham tDCS over ipsilesional-M1, within various durations and timing	+[†]	+[†]	The amount or timing of bihemispheric tDCS does not influence the amount ML.	ML: hard Paradigm: hard
Wadden, 2019[44]	Neurostimulation	Contralesional M1 vs S1 vs sham cTBS, prior to practice	+[†,‡]	NR[†]	cTBS does not enhance motor acquisition or retention, regardless of the location of stimulation	ML: hard Paradigm: hard
Zimerman, 2012[28]	Neurostimulation	Active vs sham cathodal tDCS over contralesional-M1 during learning	+[‡]	+[†,‡]	Active cathodal tDCS over contralesion-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 prinipcle of ML in clinical practice; and "paradigm" is the ease of duplicating the study paradigm in clinical settings.

[†] No significant ML group differences.

[‡] 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.[23] In contrast, the second study found that daytime napping does not enhance ML.[34] 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.[21,59] 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.[22] 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,[53] but was not significantly different from constant/blocked practice in 2 studies.[39,54] 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[29,55] compared feedback to a no-feedback control; both studies found feedback facilitated ML. Furthermore, the mode (tactile vs verbal),[56] frequency (100% vs 67%),[43] and content (reward and punishment)[32] 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.[30,31,45,51,52] All studies had participants imagine/observe functional motor tasks. Improvements in motor performance were found irrespective of timing of mental imagery[52] or if physical practice was performed.[31] One study found that longer sessions of observation and practice promoted greater motor improvements during retention testing.[30]

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.[47,48,57] 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,[37] whereas another study using a hand grasp-force task found that high-intensity interval training enhanced retention performance.[40] 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 ispislesional-M1,[26,27,33,58] a single site of anodal stimulation over ispislesional-M1,[38,50] or a single site of cathodal stimulation over contralesional-M1.[28] Most studies found a positive effect of tDCS on acquisition[27,28,50,58] and, at minimum, active stimulation helped improve short-term retention of motor skills.[26-28,58] However, 2 studies showed no significant group differences between active and sham stimulation groups.[33,38] Two studies, which included the same participants, investigated the influence of 5Hz rTMS over ipsilesional-S1 prior to task practice.[24,25] 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.[42] Two studies investigated the use of cTBS over S1 versus M1 stimulation prior to practice, neither enhanced ML greater than sham stimulation.[43,44] Finally, iTBS over the cerebellum was found to enhance motor acquisition and retention greater than sham stimulation.[35] 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,[24,25,33,50] and 10 studies received a rating of fair.[23,45,52,55] Nine studies that were assessed used the pre-post study with no control intervention tool; 7 had a good rating,[21,26-28,31,46,56] and 2 had a fair rating.[59] Finally, 11 studies were assessed using the tool for observational cohort and cross-sectional studies; 5 studies were rated good,[32,43,47,48,57] and 6 studies were rated fair.[22,29,30,49,51,53]

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

Table 5 Risk of bias using the National Institutes of Health National Heart, Lung and Blood Institute quality assessment tools

Controlled Intervention Studies

First Author, Year	Q1 Described as Randomized	Q2 Suitable Randomization	Q3 Group Allocation Concealed	Q4 Study Participants and Providers Blinded	Q5 Assessors Blinded	Q6 Groups Similar at Baseline	Q7 Dropout <20%	Q8 Difference in Dropout Between Group<15%	Q9 High Adherence to Protocols	Q10 Other Treatment Avoided/Similar in Groups	Q11 Reliable and Valid Measure-ment Tools	Q12 Sample Size Large Enough for 80% Power	Q13 Outcomes Reported /Subgroups Analyzed Prespecified	Q14 Participants Analyzed Based on Initial Group Allocation	Overall Rating
Backhaus, 2018[34]	Y	Y	Y	NA	NA	Y	N	N	N	Y	Y	N	Y	Y	Fair
Bonni, 2020[35]	Y	NR	NR	NA	NA	Y	NR	NR	Y	NR	Y	NR	Y	Y	Fair
Bonuzzi, 2020[36]	N	NA	NA	NA	NA	Y	Y	Y	Y	Y	Y	NR	Y	Y	Good
Brodie, 2014[24]	Y	Y	NR	NA	NA	Y	Y	Y	Y	Y	Y	NR	Y	Y	Good
Brodie, 2014[25]	Y	Y	NR	NA	NA	Y	Y	Y	Y	Y	Y	N	Y	Y	Good
Charalambos, 2018[37]	N	NR	NA	NA	NA	Y	NR	NR	Y	Y	Y	NR	Y	Y	Fair
Dobkin, 2010[55]	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Fair
Doost, 2019[38]	Y	Y	NR	Y	NA	Y	Y	Y	Y	Y	Y	NR	Y	Y	Good
Hamoudi, 2018[50]	Y	Y	NR	NR	NA	Y	Y	Y	Y	NR	Y	Y	Y	Y	Good
Helm, 2020[39]	Y	NR	NR	N	N	Y	NR	NR	Y	NR	Y	Y	Y	Y	Fair
Jo, 2020[54]	Y	N	N	N	N	Y	Y	Y	Y	Y	N	NR	Y	Y	Fair
Malouin, 2009[45]	Y	Y	NR	NR	Y	NR	NR	Y	Y	Y	N	Y	Y	Y	Fair
Nepveu, 2017[40]	Y	NR	NA	NA	NA	Y	Y	Y	Y	Y	Y	NR	Y	Y	Good
Neva, 2019[41]	Y	Y	N	N	Y	Y	Y	Y	Y	NR	Y	NR	Y	Y	Good
Schuster, 2012[52]	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Fair
Siengsukon, 2009[23]	Y	N	NR	NR	NA	Y	Y	Y	Y	Y	Y	N	Y	Y	Fair
Takeuchi, 2012[42]	Y	NR	NR	NA	NA	Y	NR	NR	Y	Y	NR	NR	Y	Y	Fair
Vliet, 2017[33]	Y	Y	CD	Y	Y	N	Y	Y	Y	NR	Y	Y	Y	Y	Good
Wadden, 2019[44]	Y	Y	Y	NA	NA	Y	NR	NR	Y	Y	Y	NR	Y	Y	Good

Pre-Post Studies With No Control

First Author, Year	Q1 Study Question	Q2 Eligibility Criteria and Study Population	Q3 Study Participants Representative of Clinical Population of Interest	Q4 All Eligible Participants Enrolled	Q5 Sample Size	Q6 Intervention Clearly Described	Q7 Outcome Measures Clearly Described, Valid, and Reliable	Q8 Blinding of Outcome Assessors	Q9 Follow-up Rate	Q10 Statistical Analysis	Q11 Multiple Outcome Measures	Q12 Group Level Interventions and Individual Level Outcome Efforts	Overall Rating
Bonuzzi, 2016[21]	Y	Y	Y	Y	Y	N	Y	NR	Y	Y	CD	NA	Good
Guttman, 2012[31]	y	y	y	NR	N	Y	N	N	Y	Y	Y	NA	Good
Lefebvre, 2013[27]	Y	Y	Y	NR	Y	Y	Y	Y	NR	Y	Y	NA	Good
Lefebvre, 2015[58]	Y	Y	CD	Y	Y	Y	Y	Y	CD	Y	Y	CD	Fair
Lefebvre, 2017[26]	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	NA	Good
Ploughman, 2018[56]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	NA	Good
Pohl, 2001[46]	Y	Y	Y	Y	Y	Y	Y	NA	Y	Y	Y	N	Good
Pollock, 2014[59]	Y	Y	N	NR	N	Y	Y	N	NR	N	N	NA	Fair
Zimerman, 2012[28]	Y	N	Y	NR	CD	Y	Y	Y	Y	Y	Y	NA	Good

Observational Cohort and Cross-Sectional Studies

First Author, Year	Q1 Clear Research Question/ Objective	Q2 Study Pop-ulation Defined	Q3 Participation Rate At Least 50%	Q4 All Participants From Similar Pop-ulations	Q5 Sample Size Justification or Power Calculation	Q6 Exposures Measured Prior to Outcome	Q7 Sufficient Time-frame to Get Response	Q8 Measures Different Exposure Levels	Q9 Exposure Measures Defined/Valid/ Reliable/Consistent	Q10 Exposure Assessed More Than One Time	Q11 Dependent Measures Defined/Valid/ Reliable/Consistent	Q12 Outcome Assessors Blinded	Q13 Loss to Follow- Up <20%	Q14 Key Potential Confounding Measured and Adjusted	Overall Rating
Boyd, 2003[51]	Y	Y	NR	Y	Y	NA	Y	Y	Y	NA	Y	Y	Y	Y	Good
Boyd, 2004[60]	Y	Y	CD	Y	NR	NA	Y	Y	Y	NA	Y	NR	Y	NA	Good
Boyd, 2006[50]	Y	N	NR	Y	N	NA	Y	NA	Y	Y	Y	NR	Y	Y	Good
Carey, 2007[30]	Y	NR	Y	NA	NR	Y	N	Y	N	NA	Y	NR	Y	Y	Fair
Cirstea, 2003[52]	Y	Y	NR	Y	N	NA	Y	NA	Y	NA	Y	NR	Y	Y	Fair
Orrell, 2006[22]	Y	Y	NR	Y	Y	NA	Y	Y	Y	NA	Y	NR	Y	N	Fair
Quattrocchi, 2017[33]	N	Y	Y	Y	Y	NA	Y	NA	Y	NA	Y	NR	Y	Y	Good
	Schweighofter, 2011[56]	Y	Y	NR	Y	N	NA	Y	NA	Y	NA	Y	N	Y	N
Fair															
Tretriluxana, 2014[54]	Y	N	NR	CD	NR	NA	Y	Y	Y	NA	Y	NR	NR	Y	Fair
Tretriluxana, 2015[31]	Y	Y	Y	Y	N	NA	Y	Y	Y	Y	Y	NR	Y	Y	Fair
Winstein, 1999[44]	Y	Y	NR	Y	NR	NA	Y	Y	Y	NA	Y	NR	Y	NA	Good

Abbreviations: CD, cannot determine; N, no; NA, not applicable; NR, not reported; Y, yes.

rated as easy to apply in the clinical setting and thus have clinical utility. The evidence for the effect of sleep, practice schedules, aerobic exercise, and neurostimulation on ML is less clear. Based on the additional personnel and equipment required, aerobic exercise was determined moderately difficult to apply clinically, whereas all types of neurostimulation were determined to be difficult to apply clinically.

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.[19] 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 (ie, novice vs expert) influences learning in neurotypical populations.[60] 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.[31] 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.[31]

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.[49] 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.[61] 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,[4,62] 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.[63] 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 period,[30,45,50,55] 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.[8] 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.[67] We found conflicting evidence about the effect of sleep on ML.[23,34] This conflict may be because study protocol factors (ie, time of testing[68] and task features[67]) 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 learn[59]; 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 level[60] 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.[53] This is consistent with other ML studies in neurotypical adults[73] 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.[53] This provides evidence that clinicians should consider how to disperse exercises/movements within a single therapy session. For example, for perturbation based-balance training,[75] 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 mediate 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,[43] 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.[58] 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[45] 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 is 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.[47,48,57] 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.[40] 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,[86] 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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References

1. Langhorne P, Bernhardt J, Kwakkel G. Stroke Rehabilitation. Lancet 2011;337:1693-702.
2. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. Lancet Neurol 2009;8:741-54.
3. Carr JH, Shepherd RB, eds. Movement science: foundation of physical therapy in rehabilitation, Rockville: Aspen; 1987.
4. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. Curr Opin Neurol 2006;19:84-90.
5. Schmidt RA, Lee TD, Winstein C, Wulf G, Zelaznik HN. Motor control and learning: a behavioural emphasis. 6th ed. Champaign: Human Kinetics; 2018.
6. Carr JH, Shepherd RB. A motor learning model for stroke rehabilitation. Physiother (United Kingdom) 1989;75:372-80.
7. Nelson ML, McKellar KA, Yi J, et al. Stroke rehabilitation evidence and comorbidity: a systematic scoping review of randomized controlled trials. Top Stroke Rehabil 2017;24:374-80.
8. Hebert D, Lindsay MP, McIntyre A, et al. Canadian stroke best practice recommendations: stroke rehabilitation practice guidelines, update 2015. Int J Stroke 2016;11:459-84.
9. Kitago T, Krakauer JW. Motor learning principles for neurorehabilitation. Handb Clin Neurol 2013;110:93-103.
10. Boyd LA, Vidoni ED, Wessel BD. Motor learning after stroke: is skill acquisition a prerequisite for contralesional neuroplastic change? Neurosci Lett 2010;482:21-5.
11. Winstein CJ, Schmidt RA. Reduced frequency of knowledge of results enhances motor skill learning. J Exp Psychol Learn Mem Cogn 1990;16:677-91.
12. van Vliet P, Wulf G. Extrinsic feedback for motor learning after stroke: what is the evidence? Disabil Rehabil 2006;28:831-40.
13. Maier M, Ballester BR, Duff A, Oller ED, Verschure PF. Effect of specific over nonspecific VR-based rehabilitation on poststroke motor recovery : a systematic meta-analysis. Neurorehabil Neural Repair 2019;33:112-29.
14. Maier M, Ballester BR, Verschure PF. Principles of neurorehabilitation after stroke based on motor learning and brain plasticity mechanisms. Front Syst Neurosci 2019;13:1-18.
15. Lesko LJ, Zineh I, Huang S. What is clinical utility and why should we care? Clin Pharmacol Ther 2009;88:729-33.
16. Levac D, Colquhoun H, O'Brien KK. Scoping studies: advancing the methodology. Implement Sci 2010;5:69.
17. Tricco AC, Lillie E, Zarin W, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med 2018;169:467-73.
18. Spencer AJ, Eldredge JD. Roles for librarians in systematic reviews: a scoping review. J Med Libr Assoc 2018;106:46-56.
19. Bernhardt J, Hayward KS, Kwakkel G, et al. Agreed definitions and a shared vision for new standards in stroke recovery research: the stroke recovery and rehabilitation roundtable taskforce. Neurorehabil Neural Repair 2017;31:793-9.
20. National Heart Lung and Blood Institute. Study quality assessment tools. Available at: https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools. Accessed January 30, 2019.
21. Bonuzzi GMG, Freitas TB, Corrêa UC, Freudenheim AM, Pompeu JE, Torriani-Pasin C. Learning of a postural control task by elderly post-stroke patients. Motricidade 2016;12:141-8.

22. Orrell AJ, Eves FF, Masters RSW. Motor learning of a dynamic balancing task after stroke: implicit implications for stroke rehabilitation. Phys Ther 2006;86:369-80.
23. Siengsukon CF, Boyd LA. Sleep to learn after stroke: implicit and explicit off-line motor learning. Neurosci Lett 2009;451:1-5.
24. Brodie SM, Meehan S, Borich MR, Boyd LA. 5 Hz repetitive transcranial magnetic stimulation over the ipsilesional sensory cortex enhances motor learning after stroke. Front Hum Neurosci 2014;8:143.
25. Brodie SM, Borich MR, Boyd LA. Impact of 5-Hz rTMS over the primary sensory cortex is related to white matter volume in individuals with chronic stroke. Eur J Neurosci 2014;40:3405-12.
26. Lefebvre S, Dricot L, Laloux P, et al. Increased functional connectivity one week after motor learning and tDCS in stroke patients. Neuroscience 2017;340:424-35.
27. Lefebvre S, Laloux P, Peeters A, Desfontaines P, Jamart J, Vandermeeren Y. Dual-tDCS enhances online motor skill learning and long-term retention in chronic stroke patients. Front Hum Neurosci 2013;6:1-17.
28. Zimerman M, Heise KF, Hoppe J, Cohen LG, Gerloff C, Hummel FC. Modulation of training by single-session transcranial direct current stimulation to the intact motor cortex enhances motor skill acquisition of the paretic hand. Stroke 2012;43:2185-91.
29. Carey JR, Durfee WK, Bhatt E, et al. Comparison of finger tracking versus simple movement training via telerehabiliation to alter hand function and cortical reoganization after stroke. Neurorehabil Neural Repair 2007;21:216-32.
30. Tretriluxana J, Taptong J, Chaiyawat P. Dyad training protocol on learning of bimanual cup stacking in individuals with stroke: effects of observation duration. J Med Assoc Thai 2015;98(Suppl 5):S106-12.
31. Guttman A, Burstin A, Brown R, Bril S, Dickstein R. Motor imagery practice for improving sit to stand and reaching to grasp in individuals with poststroke hemiparesis. Top Stroke Rehabil 2012;19:306-19.
32. Quattrocchi G, Greenwood R, Rothwell JC, Galea JM, Bestmann S. Reward and punishment enhance motor adaptation in stroke. J Neurol Neurosurg Psychiatry 2017;88:730-6.
33. van der Vliet R, Ribbers GM, Vandermeeren Y, Frens MA, Selles RW. BDNF Val66Met but not transcranial direct current stimulation affects motor learning after stroke. Brain Stimul 2017;10:882-92.
34. Backhaus W, Braass H, Gerloff C, Hummel FC. Can daytime napping assist the process of skills acquisition after stroke? Front Neurol 2018;9:1002.
35. Bonnì S, Motta C, Pellicciari MC, et al. Intermittent cerebellar theta burst stimulation improves visuo-motor learning in stroke patients: a pilot study. Cerebellum 2020;19:739-43.
36. Bonuzzi GMG, Freitas TB De, Palma GC, et al. Effects of the brain-damaged side after stroke on the learning of a balance task in a non-immersive virtual reality environment. Physiother Theory Pract. 2020 Feb 24 [Epub ahead of print].
37. Charalambous CC, Alcantara CC, French MA, et al. A single exercise bout and locomotor learning after stroke: physiological, behavioural, and computational outcomes. J Physiol 2018;596:1999-2016.
38. Doost MY, De Xivry JO, Herman B, et al. Learning a bimanual cooperative skill in chronic stroke under noninvasive brain stimulation: a randomized controlled trial. Neurorehabil Neural Repair 2019;33:486-98.
39. Helm EE, Pohlig RT, Kumar DS, Reisman DS. Practice structure and locomotor learning after stroke. J Neurol Phys Ther 2020;43:85-93.
40. Nepveu J-F, Thiel A, Tang A, et al. A single bout of high-intensity interval training improves motor skill retention in individuals with stroke. Neurorehabil Neural Repair 2017;31:726-35.
41. Neva JL, Brown KE, Wadden KP, Mang CS, Borich MR, Meehan SK. The effects of five sessions of continuous theta burst stimulation over contralesional sensorimotor cortex paired with paretic skilled motor practice in people with chronic stroke. 2019;37:273-90.
42. Takeuchi N, Tada T. Low-frequency repetitive TMS plus anodal transcranial DCS prevents transient decline in bimanual movement induced by contralesional inhibitory rTMS after stroke. Neurorehabil Neural Repair 2012;26:988-98.
43. Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. Neuropsychologia 1999;37:975-87.
44. Wadden KP, Peters S, Borich MR, et al. White matter biomarkers associated with motor change in individuals with stroke: a continuous theta burst stimulation study. Neural Plast 2019;2019:7092496.
45. Malouin F, Richards CL, Durand A, Doyon J. Added value of mental practice combined with a small amount of physical practice on the relearning of rising and sitting post-stroke: a pilot study. J Neurol Phys Ther 2009;33:195-202.
46. Pohl PS, Mcdowd JM, Filion DL, Richards LG, Stiers W. Implicit learning of a perceptual-motor skill after stroke. Phys Ther 2001;81:1780-9.
47. Boyd LA, Winstein CJ. Explicit information interferes with implicit motor learning of both continuous and discrete movement tasks after stroke. J Neurol Phys Ther 2006;30:46-57.
48. Boyd LA, Winstein CJ. Impact of explicit information on implicit motor-seqeunce learning following middle cerebral artery stroke. Phys Ther 2003;83:976-89.
49. Cirstea MC, Ptito A, Levin MF. Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. Exp Brain Res 2003;152:476-88.
50. Hamoudi M, Schambra HM, Fritsch B, et al. Transcranial direct current stimulation enhances motor skill learning but not generalization in chronic stroke. Neurorehabil Neural Repair 2018;32:295-308.
51. Tretriluxana J, Khachoroen S, Hiengkaew V, Prayoonwiwat N. Learning of the bimanual cup-stacking task in individuals with chronic stroke improved with dyad training protocol. J Med Assoc Thail 2014;97(Suppl 7):S39-44.
52. Schuster C, Butler J, Andrews B, Kischka U, Ettlin T. Comparison of embedded and added motor imagery training in patients after stroke: results of a randomised controlled pilot trial. Trials 2012;13:11.
53. Schweighofer N, Lee J-Y, Goh H-T, et al. Mechanisms of the contextual interference effect in individuals poststroke. J Neurophysiol 2011;106:2632-41.
54. Jo E, Noh D, Kam K. Human movement science effects of contextual interference on feeding training in patients with stroke. Hum Mov Sci 2020;69:102560.
55. Dobkin BH, Plummer-D'Amato P, Elashoff R, Lee J. International randomized clinical trial, stroke inpatient rehabilitation with reinforcement of walking speed (SIRROWS), improves outcomes. Neurorehabil Neural Repair 2010;24:235-42.
56. Ploughman M, Shears J, Quinton S, et al. Therapists' cues influence lower limb muscle activation and kinematics during gait training in subacute stroke. Disabil Rehabil 2018;40:3156-63.
57. Boyd LA, Winstein CJ. Providing explicit information disrupts implicit motor learning after basal ganglia stroke. Learn Mem 2004;11:388-96.
58. Lefebvre S, Dricot L, Laloux P, et al. Neural substrates underlying stimulation-enhanced motor skill learning after stroke. Brain 2015;138:149-63.
59. Pollock CL, Boyd LA, Hunt MA, Garland SJ. Use of the challenge point framework to guide motor learning of stepping reactions for improved balance control in people with stroke: a case series. Phys Ther 2014;94:562-70.

60. Guadagnoll MA, Lee TD. Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. J Mot Behav 2004;36:212–24.
61. Jonsdottir J, Recalcati M, Rabuffetti M, Casiraghi A, Boccardi S, Ferrarin M. Functional resources to increase gait speed in people with stroke: strategies adopted compared to healthy controls. Gait Posture 2009;29:355–9.
62. Lohse KR, Lang CE, Boyd LA. Is more better? Using metadata to explore dose-response relationships in stroke rehabilitation. Stroke 2014;45:2053–8.
63. Lang CE, MacDonald JR, Reisman DS, et al. Observation of amounts of movement practice provided during stroke rehabilitation. Arch Phys Med Rehabil 2009;90:1692–8.
64. Soderstrom NC, Bjork RA. Learning versus performance: an integrative review. Perspect Psychol Sci 2015;10:176–99.
65. Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: a review and critical reappraisal. Psychol Bull 1984;95:355–86.
66. Winfred A, Winston B, Stanush PL, McNelly TL. Factors that influence skill decay and retention: a quantitative review and analysis. Hum Perform 1998;11:57–101.
67. Gudberg C, Johansen-Berg H. Sleep and motor learning: implications for physical rehabilitation after stroke. Front Neurol 2015;6:241.
68. Pan SC, Rickard TC. Sleep and motor learning: is there room for consolidation? 2015;141:812-34.
69. Backhaus W, Kempe S, Hummel FC. The effect of sleep on motor learning in the aging and stroke population — a systematic review. Restor Neurol Neurosci 2016;34:153–64.
70. Page SJ, Gater DR, Bach-Y-Rita P. Reconsidering the motor recovery plateau in stroke rehabilitation. Arch Phys Med Rehabil 2004;85:1377–81.
71. Hart SG. NASA-task load index (NASA-TLX); 20 years later. In Proceedings of the human factors and ergonomics society annual meeting 2006 Oct (Vol. 50, No. 9, pp. 904-908). Sage CA: Los Angeles, CA: Sage publications.
72. Akizuki K, Ohashi Y. Measurement of functional task difficulty during motor learning: what level of difficulty corresponds to the optimal challenge point? Hum Mov Sci 2015;43:107–17.
73. Shea JB, Morgan RL. Contextual interference effects on the acquisition, retention, and transfer of a motor skill. J Exp Psychol Hum Learn Mem 1979;5:179–87.
74. Hanlon RE. Motor learning following unilateral stroke. Arch Phys Med Rehabil 1996;77:811–5.
75. Mansfield A, Aqui A, Danells CJ, et al. Does perturbation-based balance training prevent falls among individuals with chronic stroke? A randomised controlled trial. BMJ Open 2018;8:e021510.
76. Gatti R, Tettamanti A, Gough P, Riboldi E, Marinoni L, Buccino G. Action observation versus motor imagery in learning a complex motor task: a short reivew of liteature and a kinematics study. Neurosci Lett 2013;540:37–42.
77. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. Med Educ 2010;44:75-84.
78. Stefan K, Cohen LG, Duque J, et al. Formation of a motor memory by action observation. J Neurosci 2005;25:9339–46.
79. Boyd LA, Quaney BM, Pohl PS, Winstein CJ. Learning implicitly: effects of task and severity after stroke. Neurorehabil Neural Repair 2007;21:444–54.
80. Klintsova AY, Dickson E, Yoshida R, Greenough WT. Altered expression of BDNF and its high-affinity receptor TrkB in response to complex motor learning and moderate exercise. Brain Res 2004;1028:92–104.
81. Skriver K, Roig M, Lundbye-jensen J, et al. Neurobiology of learning and memory acute exercise improves motor memory: exploring potential biomarkers. Neurobiol Learn Mem 2014;116:46-58.
82. Mang CS, Campbell KL, Ross CJD, Boyd LA. Promoting neuroplasticity for motor rehabilitation after stroke: considering the effects of aerobic exercise and genetic variation on brain-derived neurotrophic factor. Phys Ther 2013;93:1707–16.
83. Mahon S, Parmar P, Barker-Collo S, et al. Determinants, prevalence, and trajectory of long-term post-stroke cognitive impairment: results from a 4-year follow-up of the ARCOS-IV study. Neuroepidemiology 2017;49:129–34.
84. Jokinen H, Melkas S, Ylikoski R, et al. Post-stroke cognitive impairment is common even after successful clinical recovery. Eur J Neurol 2015;22:1288–94.
85. Bramley A, Rodriguez AA, Chen J, et al. Lessons about motor learning: how is motor learning taught in physical therapy programmes across Canada? Physiother Can 2018;70:365–72.
86. Slade SC, Dionne CE, Underwood M, Buchbinder R. Consensus on exercise reporting template (CERT): explanation and elaboration statement. Br J Sports Med 2016;50:1428–37.