Improving Movement Automaticity and Dual-Task Performance in People with Stroke:

A Change of Focus?

Elmar Kal

IMPROVING MOVEMENT AUTOMATICITY AND DUAL-TASK PERFORMANCE IN PEOPLE WITH STROKE A CHANGE OF FOCUS?

Elmar Christiaan Kal

This PhD thesis was embedded within Amsterdam Movement Sciences research institute, at the Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, the Netherlands. The work presented in this thesis was carried out in collaboration with the Research & Development department of Rehabilitation Centre Heliomare, Wijk aan Zee, the Netherlands.

The printing of this thesis was financially supported by Heliomare, Amsterdam Movement Sciences, the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit, the Arnold Oosterbaan Hersenstichting and ProCare B.V.

Financial support by the Dutch Heart Foundation for the publication of this thesis is gratefully acknowledged.

Cover design: Jenny Schavemaker
Layout: Proefschriftmaken.nl
Printing: Proefschriftmaken.nl
ISBN: 978-94-6380-052-5

VRIJE UNIVERSITEIT

IMPROVING MOVEMENT AUTOMATICITY AND DUAL-TASK PERFORMANCE IN PEOPLE WITH STROKE

A CHANGE OF FOCUS?

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor of Philosophy
aan de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. V. Subramaniam,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Gedrags- en Bewegingswetenschappen
op donderdag 29 november 2018 om 11.45 uur
in de aula van de universiteit,
De Boelelaan 1105

door

Elmar Christiaan Kal

geboren te Haarlem

promotoren: prof.dr. E.J.A. Scherder
prof.dr. C.A.M. van Bennekom

copromotoren: dr. G.J. van der Kamp
dr. J.H.P. Houdijk

Table of contents

Chapter 1

General introduction

1. Introduction

Stroke occurs when the supply of blood to part of the brain is disrupted, and brain tissue degenerates as a result of a lack of oxygen and nutrient.[1] Infarctions and haemorrhaging of cerebral arteries are the two main types of stroke, but the former are far more prevalent (roughly 90% vs 10%, respectively).[2] In the Netherlands alone, the prevalence of stroke is estimated to be over 300.000, with approximately 41.000 newly registered cases each year.[3] Stroke is a major cause of death and disability: it is estimated that worldwide around 12% of all deaths in 2015 were the consequence of stroke.[1] For the approximately two-thirds of patients who do survive the first month post-stroke[4] its sequelae are often highly debilitating for daily functioning.[3] This occurs because stroke can profoundly impact motor (e.g., loss of muscle strength and coordination),[5] cognitive (e.g., deficits in language, attention, and memory),[6] and/or neuropsychiatric functioning (e.g. depression, fatigue, personality changes).[7] Patients therefore often receive intensive, multidisciplinary rehabilitative care to improve their (independence of) daily functioning and quality of life.

This thesis focuses on one particular problem at the interface of motor and cognitive functioning, one that many stroke patients experience and that many therapists find difficult to address: An impaired ability to concurrently perform additional cognitive tasks during moving – so-called motor-cognitive dual-tasking.[8] In this general introduction I will first highlight the impact of dual-task impairments on patients' daily functioning. Next, I will shortly go into stroke patients' specific impairments in dual-tasking in light of the dominant views on (successful) dual-task performance, and describe the possible interventions that might follow from these. This introduction will close with an argumentation as to why one specific intervention called implicit motor learning might be particularly effective to improve dual-tasking in people with stroke. This proposition will be further scrutinized in detail in this thesis.

1.1. Impaired dual-tasking after stroke

Although people often may not be aware of it, performing dual-tasks is integral to daily life. During every-day tasks like crossing a street, for instance, we concurrently need to monitor the environment for upcoming cars or cyclists, and sometimes also talk with someone else, listen to music, or – increasingly so – busy ourselves with our smartphone. Fortunately, for many (healthy) people, walking is largely automated* such that dual-task performance can generally be achieved relatively safely and without much effort. Stroke patients, however, often have great difficulty with performing dual-tasks while standing or walking. In fact,

* Please note that gait is likely never fully automated. Even in young, fit, healthy adults walking will require some level of conscious control (Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Post 2002; 16(1): 1-14.)

although most stroke patients regain some degree of walking ability,[9] their capacity for dual-tasking does not substantially improve throughout rehabilitation.[8] Postural control[10] and gait[8] often strongly deteriorate when an additional cognitive task is to be performed, even years after discharge from rehabilitation.[11–13] This has significant repercussions for patients' mobility, safety, and daily functioning.[14] For example, many stroke patients can no longer walk fast enough to safely cross a street[15] when required to perform an additional cognitive task.[13,16] Further, a reduced dual-tasking ability may also increase their risk of falling.[17,18]

1.2. Underlying mechanisms of successful and impaired dual-tasking after stroke

In order to find interventions to address patients' dual-tasking impairments, it is important to consider the mechanisms at play. The dominant perspective on explaining dual-task performance revolves around the so-called capacity sharing hypothesis[19–21] and working memory model.[22] Shortly, capacity sharing posits that a performer's attentional resources are inherently limited, and that during dual-tasking both tasks thus compete for these resources. Hence, a prerequisite for successful dual-task performance is that the performer's attentional capacity is large enough to accommodate the combined task demands.[19] By itself however, a large attentional capacity is not sufficient. The performer also needs to be able to appropriately allocate the available attentional resources to each of the two tasks – a role which Baddeley assigned to the "central executive" in his working memory model.[22,23]

In people with stroke, the abovementioned prerequisites for successful dual-task performance are often not met. First, patients' capacity is often limited - up to half of all patients experiences persistent attentional deficits,[24,25] primarily in the form of reduced information processing speed and impaired sustained and selective attention.[26] Further, impairments of executive function are highly prevalent as well.[24,27] Adding to this, stroke patients seem generally strongly predisposed to consciously control and monitor their movements, far more so than healthy peers.[28,29] As a result, for many patients motor skills such as walking require a substantial amount of attentional capacity, leaving fewer resources available for the performance of additional tasks.

Put together, dual-tasking impairments after stroke may arise through a combination of increased demands placed on a reduced attentional capacity that itself often cannot be deployed optimally.

1.3. Possible interventions to improve dual-tasking after stroke?

Based on the above, there are two logical ways to address dual-tasking impairments after stroke. The first is to improve patients' working memory *functioning*, by increasing their available attentional resources and/or optimize their ability to strategically deploy these. The last decade has seen a surge in studies that investigated whether dedicated cognitive training programs result in generic improvements in attention and working memory capacity. Although initial results seemed promising,[30,31] recent systematic reviews[32,33] concluded that interventions are generally not effective. Improvements are short-lived, and largely restricted to the tasks trained. Melby-Lervåg et al.[32] therefore proposed that improving particular working memory functions – such as dual-tasking – can only be achieved with highly task-specific interventions.

A prime example of such a highly task-specific intervention is dual-task training. The rationale is that by practicing two tasks simultaneously, patients can improve their ability to strategically divide attention during moving.[34] Preliminary evidence does suggest beneficial effects of dual-task training in stroke.[35,36] However, improvements do not seem to generalize beyond the practiced dual-task combinations. For example, in the case-series by Plummer et al.[37] sub-acute stroke patients completed 12 sessions of gait-related exercises (e.g., walking with narrow base of support, crossing obstacles) with simultaneous cognitive tasks (e.g., naming as many words as possible starting with specific letter). Patients' gait speed was significantly more robust to dual-task interference after the intervention compared to baseline, but mostly in dual-task conditions that involved executive function – similar to the practiced cognitive dual-tasks. No or minor improvements were observed in untrained visuospatial and spontaneous speech dual-task conditions. Limited transfer of training effects, which is also a common finding in healthy elderly,[38,39] is a significant drawback: It implies that patients need to practice each motor task in combination with the potentially very large number of dual-task combinations that are relevant to daily life. Another limitation of dual-task training is that the high task complexity makes it less suitable for people with severe cognitive or motor deficits.[35]

This leads us to an alternative approach to enhance dual-tasking, namely to reduce the *load* placed on patients' working memory by increasing their automaticity of movement. The rationale is simple: when motor skills become more automatic, motor performance requires less working memory involvement. As a result, more residual capacity remains available for the performance of a second (motor or cognitive) task. In theory, when compared with dual-task training, a main benefit of this automatization approach is that it should improve dual-tasking across a wide range of dual-task combinations. Also, interventions that promote automatization should be less cognitively demanding, making them potentially more suitable for patients with severe cognitive deficits.

In spite of the rationale presented above, in current rehabilitation practice automatization of motor skills may actually be hindered. This because there seems to be widespread use of explicit motor learning strategies. Such explicit learning heavily relies on the processing and storing of the movement-related rules conveyed in the therapists' instructions – a process that is highly working memory dependent.[40,41] For example, therapists have been reported to predominantly use verbal instructions and feedback that prescribe how movements should be performed. This stimulates patients to consciously control movements.[42,43] The high frequency of explicit learning sessions during rehabilitation is thought to contribute to patients' strong conscious control tendencies, and thereby may exacerbate their dual-task impairments.[28]

This thesis explores the merits of the alternative *implicit motor learning*[41] approach for stroke rehabilitation. Implicit motor learning is considered to require no or minimal working memory involvement,[40,44] and thereby result in relatively automatic movements that are robust to dual-task interference. However, notwithstanding its theoretical potential, very little is known about implicit motor learning in people with stroke. Before entering studies on implicit motor learning in people with stroke, the remainder of this introduction describes the core concept of implicit motor learning as well as converging lines of evidence in healthy adults and elderly that indicate that implicit motor learning fosters movement automaticity and, consequently, dual-task performance.

2. What is implicit motor learning?

The concept of implicit motor learning is best understood in relation to traditional views on skill acquisition.[45,46] These hold that in the early verbal-cognitive phase of motor learning, motor performance requires considerable involvement of a performer's working memory; adult novices must accrue and employ verbal movement-related rules and strategies to consciously control motor performance. In the course of learning, however, control gradually becomes less dependent on declarative knowledge and instead increasingly relies on procedural knowledge that directly links task-relevant information to the desired motor response.[45] Since procedural knowledge is inaccessible for consciousness, motor control becomes less reliant on working memory contributions. Finally, after extensive practice the automatic phase is reached, in which motor control has become fully procedural. This type of learning – involving a shift in motor control from based on declarative toward based on procedural knowledge – is typically referred to as explicit motor learning.[47]

When learning is intentional and unconstrained, adult learners typically engage in explicit motor learning from learning onset.[41,48,49] Nonetheless, motor learning can also be *implicit* right from the beginning of learning.[48,50,51] In contrast to explicit motor learning, implicit motor learning is characterized by improvements in motor performance with no or minimal use and aggregation of declarative movement-related knowledge.[47] Rather, performance improvements are the result of direct shaping and reinforcing of task-relevant information-movement linkages.[52] Thus, when learning a movement implicitly, one effectively 'skips' the declarative phase of learning and directly accrues procedural knowledge of the skill instead. As a consequence, implicit motor learning is presumed to not or only minimally load working memory.[40,41,48] This should benefit dual-task performance, as a larger share of capacity can be deployed for the execution of a secondary task than with explicit learning.

3. Implicit motor learning and its relation to working memory and dual-task performance: evidence from healthy adults and elderly

If implicit motor learning indeed results in (largely) automated motor control, empirical evidence should show that implicit learning is not dependent on working memory involvement. In line with this, different strands of evidence in healthy adults and elderly indeed show that: 1) preventing involvement of working memory during skill-acquisition is key to inducing implicit motor learning; 2) compared to explicit motor learning, the neural correlates of implicit motor learning overlap less with those underlying executive working memory control; 3) the rate of implicit motor learning is not related to working memory capacity; and most importantly 4) implicitly acquired motor skills are often less affected by performance of a concurrent task. These findings will be discussed in more detail below.

3.1. Minimizing working memory involvement is essential to induce implicit motor learning

The hallmark of implicit motor learning is that, although learners show substantial improvements in motor skill, they are generally remarkably unable to describe how they perform the learned skill.[41,51] This relative absence of declarative movement-related knowledge after practice suggests that there was minimal conscious processing of verbal rules of movement by working memory during practice.[53] In line with this, all paradigms that have been found to successfully induce implicit motor learning specifically try to prevent working memory from processing movement-related rules during skill acquisition. A classic example is unintentional or incidental learning, such as in the serial reaction time (SRT) task.[51] During this task, learners unknowingly practice a sequence of key-presses. Implicit learning is evidenced by the fact that reaction times shorten on the practiced repeated sequences, but not on randomly presented stimuli.[40,51] Yet, despite their improvements in performance, learners generally are unable to verbally describe how they perform the learned task: They usually cannot recognize or explicitly reproduce the sequence they just learned.[51]

Arguably, the SRT task only involves fairly simple movements (in terms of their dynamics), whereas stroke rehabilitation usually concerns more complex skills such as sit-to-stand transfers or balance tasks. Pure implicit learning may not be achievable for such skills, as learners likely will always have some explicit knowledge of how they should perform the task at hand. However, several paradigms have been validated that minimize conscious involvement during learning of more complex functional tasks. The following interventions are agreed upon to yield most reliable implicit learning effects:[47] minimizing errors during practice such that learners do not engage in working memory demanding hypothesis-testing behavior (errorless learning),[48] instructing patients with an analogy that encapsulates all relevant movement-related information (analogy learning),[54,55] performing an attention-demanding secondary task during practice to minimize conscious control of the motor task (dual-task learning),[41,55] or triggering learners to focus on the effects of their movements (external focus learning).[56,57] In this thesis I will primarily focus on the current application and effectiveness of external focus instructions in motor learning in stroke rehabilitation.

3.2. Neural network underlying working memory overlaps more with explicit than with implicit motor learning

The neural network supporting working memory seems to be more involved in explicit motor learning than in implicit motor learning. Specifically, a fronto-striatal network is considered to be central to working memory function (see Figure 1.1).[58,59] Within this network, the prefrontal cortex functions as 'central executive' by modulating activity in other brain areas in order to enhance processing of task-relevant information. Based on the top-down input from the prefrontal cortex, the striatum (part of the basal ganglia) assists in this process, by filtering out task-irrelevant information.[60] It is highly task-dependent what other brain networks are "plugged into" this fronto-striatal network during working memory tasks. Verbal working memory tasks, for instance, mainly activate left-lateralized areas that are also engaged in phonological processing, whereas spatial tasks predominantly activate right-lateralized areas involved in visuospatial processing.[58,59]

Recently, a meta-analysis of functional imaging studies into motor learning in healthy adults has identified a cortico-striatal-cerebellar network to underlie motor skill acquisition (Figure 1.1).[61] While this network encompasses both implicit and explicit motor learning, these two learning modes differ in terms of their relative reliance on neural nodes within this network. That is, while the basal ganglia are considered to be more strongly involved in implicit motor learning,[52,62] explicit motor learning more heavily involves activity of the (dorsolateral) prefrontal[63–65] and premotor cortex.[66,67] Considering the executive role of the prefrontal cortex in working memory function, this indicates that top-down working memory control is less involved in implicit motor learning than in explicit motor learning. This is corroborated by EEG-studies that showed that explicit motor learning is associated with greater coherence between left-lateralized temporal areas involved in verbal-analytical processing and frontal motor areas involved in motor planning compared to implicit learning.[68,69]

3.3. Scores on working memory tests do not predict rate of implicit motor learning

Support for the working memory independence of implicit motor learning is also grounded in observations that learner's working memory capacity is not associated with the rate of implicit motor learning, while it does predict the rate of explicit learning. For instance, several studies have investigated the relation between improvements on the SRT task and neuropsychological working memory assessments. A recent review of these studies shows that working memory capacity positively correlates with improvement on the SRT task only after explicit motor learning, but not after implicit motor learning.[40] These findings are corroborated by observations that, although working memory capacity decreases with age,[70] this deficit seems to primarily affect elderly's explicit motor learning ability, while leaving implicit motor learning relatively intact.[71] For instance, Chauvel and co-workers[72] trained healthy young and elderly participants on a golf-putting task either implicitly through errorless learning or explicitly through error-prone learning. Working memory capacity of the elderly participants was significantly reduced compared to a young control group. At the end of training, the group of elderly participants who had engaged in explicit motor learning was outperformed by their younger counterparts both in single- and dual-task conditions. By contrast, after implicit motor learning, elderly and young participants showed equal performance improvements. This suggests that reduced working memory capacity primarily impacted explicit motor learning, rather than implicit motor learning.[cf 73]

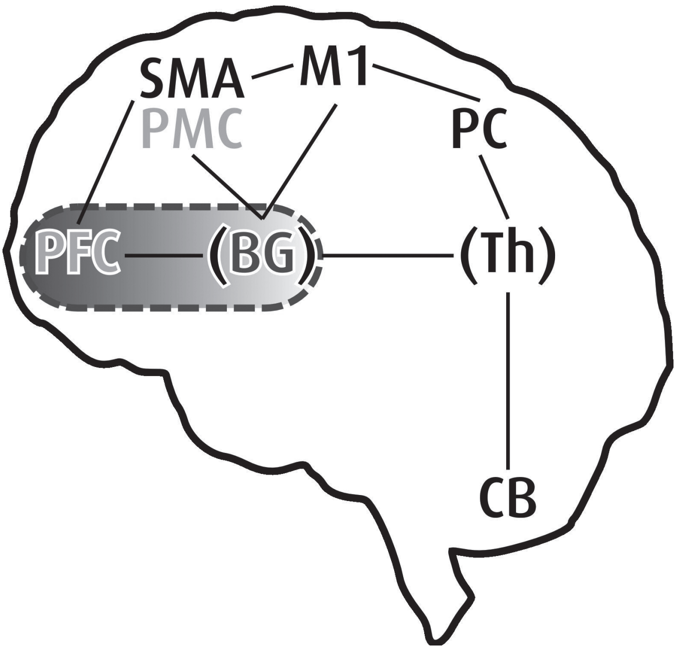


Figure 1.1. Schematic representation of the cortico-striatal-cerebellar network underlying motor learning in general[35]. Black interconnecting lines represent the functional connections within this network, and are not intended to be naturalistic representations of functional and anatomical interconnections. Neural nodes most active during explicit motor learning – highlighted in light grey – are the prefrontal cortex (PFC) and premotor cortex (PMC). The basal ganglia (BG) are especially active during implicit motor learning (highlighted in dark grey). The core of the fronto-striatal network of working memory (grey box) is superimposed on the motor learning network. Although working memory's network overlaps both with implicit (BG) and explicit (PFC) motor learning, explicit motor learning's reliance on PFC activity indicates greater reliance on executive working memory control. NB: BG = basal ganglia; CB = cerebellum; PFC = prefrontal cortex; M1 = primary motor cortex; PC = parietal cortex; PMC = premotor cortex; SMA = supplementary motor area; Th = Thalamus; () = subcortical structure

3.4. Implicit motor learning is associated with better dual-task performance

Finally, in healthy adults it has frequently been reported that the performance of implicitly acquired motor skills is robust to concurrent performance of a wide variety of cognitive tasks. Examples include counting aloud backwards during basketball shooting[54] and table tennis forehand strokes,[55] tone-counting while golf-putting,[56] and random-letter generation during rugby passing.[74] For example, Lam et al.[54] trained novice participants on a basketball free throw task, either implicitly through analogy learning by instructing them to shoot as if putting cookies in a jar on a high shelf, or explicitly by instructing them with several movement-related rules. Although both groups showed similar improvements in throwing accuracy in single task conditions, only implicit learners' performance was unaffected when they simultaneously needed to count backward in threes. Because counting accuracy and speed was similar in both groups, this difference in dual-task ability could not be attributed to differences in task-prioritization.

4. Outline of the present thesis

Recapitulating, in healthy adults there is converging evidence that implicit motor learning interventions minimally tax working memory, especially when compared to explicit motor learning interventions. Most importantly, implicit motor learning seems to result in superior dual-task performance. Nonetheless, very little is known about implicit motor learning in people with stroke. For instance, it is unclear whether stroke patients' capacity for implicit motor learning is preserved, and to what extent this applies to certain subgroups of patients. Also, there have been virtually no controlled studies that directly compared the effects of explicit and implicit interventions on motor learning and performance after stroke.[cf 75]

Hence, the main aim of this thesis is to address these issues, and explore the potential of implicit motor learning interventions as a means to improve movement automaticity and dual-task performance in rehabilitation after stroke. For a comprehensive assessment I aim to (1) systematically review the current state of the evidence regarding implicit motor learning in healthy adults and patients with stroke, (2) observe how implicit and explicit motor learning strategies are currently applied within rehabilitation practice, and (3) evaluate the effects of one specific implicit motor learning intervention in people with stroke, and explore the relation with specific individual patient characteristics. Hence, the thesis is divided in three main parts.

In the first part, I critically evaluate the current state of the evidence regarding the effectiveness of implicit motor learning interventions in healthy adults and stroke rehabilitation. Specifically, the systematic review described in **Chapter 2** assesses the effectiveness of four widely-accepted implicit motor learning interventions (analogy-, errorless-, dual-task-, and external focus learning) for improving movement automaticity and dual-task performance in healthy adults. In **Chapter 3** an additional systematic review to is performed to determine whether the ability for implicit motor learning is actually preserved after stroke.

The second part of this thesis focuses on the current practices in stroke rehabilitation. The aim is to determine how patients and therapists use explicit and implicit strategies during rehabilitation. To this end, in **Chapter 4** I validated a self-report measure of stroke patients' inclination to consciously control their movements in daily life. Subsequently, the cross-sectional study described in **Chapter 5** investigates the relation between patients' conscious control preferences and their ability to perform motor-cognitive dual-tasks. In **Chapter 6**, it is determined how often physical therapists use instructions and feedback that promote explicit (internal focus) or implicit (external focus) motor learning during inpatient rehabilitation therapy. I also explore whether therapists adapt their use of these strategies based on specific patient characteristics, such as their conscious motor control preferences, and motor and cognitive functioning.

In the final and third part of this thesis the actual effects of implicit learning on dual-tasking in healthy adults and people with stroke are assessed. One particular implicit motor learning intervention is investigated: learning using external focus instructions. This particular intervention is chosen because it is the most widely used intervention in sports research and practice,[57,76,77] and is currently gaining significant attention in neurorehabilitation education and practice as well.[78–80] Further – if found to be effective – external focus learning would be a low-cost and easily implementable tool for daily practice; in essence, therapists would only need to change the wording of their instructions. Of note though, there is some debate as to whether external focus learning induces implicit learning.[47] I therefore first perform a comprehensive analysis of the effects of external focus instructions on movement automaticity and dual-task performance during leg-stepping in healthy adults in **Chapter 7**. In **Chapter 8** this same paradigm is used to determine the direct effects of external focus instructions on leg-stepping performance and dual-tasking in chronic stroke patients. Finally, in **Chapter 9** a randomized controlled trial is run to compare the effects of external and internal focus instructions on learning a new balance task in stroke patients involved in inpatient rehabilitation. The effects on single- and dual-task performance are evaluated. Additionally, both in **Chapters 8 and 9** it is investigated whether specific patient factors such as motor and cognitive functioning determined whether patients benefit most from implicit (external focus) or explicit (internal focus) motor learning interventions.

Chapter 10 (the epilogue) summarizes the results of the studies performed, and discusses the implications of the findings of this thesis for clinical practice and future research.

Chapter 2

Does implicit motor learning lead to greater automatization of motor skills compared to explicit motor learning? A systematic review

Elmar Kal
Rens Prosée
Marinus Winters
John van der Kamp

PLoS One 13(9): e0203591

Abstract

Background: Implicit motor learning is considered to be particularly effective for learning sports-related motor skills. It should foster movement automaticity and thereby facilitate performance in multitasking and high-pressure environments. To scrutinize this hypothesis, we systematically reviewed all studies that compared the degree of automatization achieved (as indicated by dual-task performance) after implicit compared to explicit interventions for sports-related motor tasks.

Methods: For this systematic review (CRD42016038249) conventional (MEDLINE, CENTRAL, Embase, PsycINFO, SportDiscus, Web of Science) and grey literature were searched. Two reviewers independently screened reports, extracted data, and performed risk of bias assessment. Implicit interventions of interest were analogy-, errorless-, dual-task-, and external focus learning. Data analysis involved descriptive synthesis of group comparisons on absolute motor dual-task (DT) performance, and motor DT performance relative to single-task motor performance (motor DTCs).

Results: Of the 4125 reports identified, we included 25 controlled trials that described 39 implicit-explicit group comparisons. Risk of bias was unclear across trials. Most comparisons did not show group differences. Some comparisons showed superior absolute motor DT performance (N=2), superior motor DTCs (N=4), or both (N=3) for the implicit compared to the explicit group. The explicit group showed superior absolute motor DT performance in two comparisons.

Conclusions: Most comparisons did not show group differences in automaticity. The remaining comparisons leaned more toward a greater degree of movement automaticity after implicit learning than explicit learning. However, due to an overall unclear risk of bias the strength of the evidence is level 3. Motor learning-specific guidelines for design and especially reporting are warranted to further strengthen the evidence and facilitate low-risk-of-bias trials.

1. Introduction

The prospect for enhancing motor skill learning is exhilarating for practitioners in sports, rehabilitation, and physical education. Accordingly, when implicit learning interventions were proposed in handbooks of coaching and sport psychology[41,77,81,82] as alternative to traditional explicit instruction-based learning methods, these were readily adopted in sports practice (e.g. football,[83] soccer,[84] and baseball[85]). The more traditional methods presume that motor learning necessarily progresses from an initial verbal-cognitive phase, during which a learner gains declarative knowledge about the technicalities of movement skill (i.e., regularities and facts of movement execution) to increase performance, to a final autonomous phase, in which the skill has become an automatized, procedural routine and the learner is barely aware of movement execution.[45,46] This mode of learning is generally referred to as *explicit* learning: "… learning which generates verbal knowledge of movement performance (e.g. facts and rules), involves cognitive stages within the learning process and is dependent on working memory involvement"[47](18, p.5).

By contrast, implicit learning methods take as starting point that such an initial cognitive phase of declarative knowledge accrual is not mandatory. Instead, motor skill acquisition would involve direct accumulation of procedural knowledge, which is inaccessible for consciousness and is not dependent on working memory processing. Learners generally are unable to verbally describe the technicalities of the skill.[41,47,49,86] Thus, motor skills that are learned implicitly are thought to be less reliant on declarative knowledge compared to skills that are learned explicitly,[49] and instead more strongly capitalize on automatic processes.[47,72] In other words, after implicit learning motor control should be characterized by a greater degree of automaticity or, since they are two sides of the same coin, by reduced conscious control. This should be particularly evident in early learning, given that with protracted practice also explicit motor learning would eventually culminate in automatized motor control (see Figure 2.1).

Automatized motor skills are less easily disturbed when the performer's cognitive resources are compromised, for instance, due to fatigue or pressure or when concurrent tasks are performed. Especially dual-tasking has been exploited by researchers to examine the degree of movement automaticity achieved, or conversely, the degree of conscious control still required.[49,72,86–88] The tenet is that the degree of automaticity is proportional to the disruption caused by cognitively demanding dual-tasks: The more automatized the motor skill, the more robust performance is in dual-task conditions.[19] A critical prediction therefore is that implicit learning results in superior dual-task performance compared to explicit motor learning, already after short practice periods.

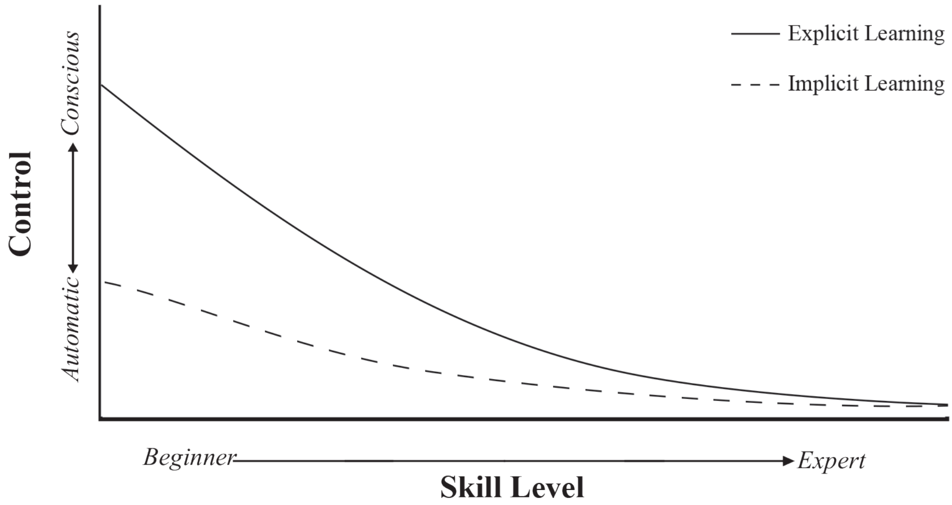


Figure 2.1. Schematic representation of the relation between implicit and explicit motor learning and conscious control/automatic control as a function of skill level. With explicit learning (solid line), motor control is highly cognitively demanding at the start of learning (in what Fitts and Posner called the verbal-cognitive stage). With implicit learning (dashed line), motor control is relatively less dependent on conscious control, and hence more automatic right from the start of learning. As skill acquisition unfolds both explicit and implicit learning will result in more and more automated motor control, and eventually converge. By measuring dual-task performance the degree of automaticity achieved can be measured.[19,86,87] Please note that the model also takes into account that skill level and automaticity are tightly related, but not interchangeable entities (i.e., skill acquisition involves more than just automating motor control).[89,90] For the same level of skill performers may substantially differ in terms of the degree of conscious/automatic control involved. On the other hand, skill level and automaticity generally co-develop with practice. Hence, skill level is an important confounder when assessing automaticity of movement.

The presumed greater automatization of motor skills after implicit motor learning bears great significance. In sports, maintaining performance in face of highly demanding dual-task situations is key to success (e.g., simultaneously monitoring game tactics and hitting a drop shot in tennis) and might even diminish risk of (re-)injury.[91,92] Moreover, motor performance should be more resilient to break down in fatiguing or high pressure situations[41] – i.e., when the athlete does not accumulate explicit knowledge early in learning, he/she will be less likely to de-automatize motor performance by falling back on (or "reinvest") such knowledge in these situations.[93] Hence, implicit motor learning methods have gained increasing interest among sport coaches. It is recommended in handbooks of sport psychology[77,82,94] and implicit motor learning principles are now increasingly applied in (inter-)national sports (e.g. football,[83] soccer,[84] and baseball[85]). Similar developments have been signaled in rehabilitation.[78,79,95]

Given its potential significance to sports science and practice, it is important to verify whether implicit motor learning indeed results in a greater degree of movement automaticity relative to explicit learning. Although individual research papers seem to support this claim, a systematic review is lacking. Hence, our aim here was to perform a comprehensive systematic review comparing the degree of movement automatization achieved after implicit and explicit motor learning interventions of sports tasks in healthy adults. Automaticity of movement was operationalized as motor skill performance during dual-tasking, probed on a separate test after the explicit or implicit learning interventions were terminated. Two aspects of dual-task performance were investigated, namely (1) absolute motor performance in dual-task conditions and (2) the robustness of motor performance to dual-task interference (i.e., the relative difference in performance between single- and dual-task conditions, so-called motor dual-task costs). If implicitly learned skills are indeed more automatic we should find higher absolute motor dual-task performance and lower motor dual-task costs for the implicit groups compared to explicit groups. In addition to summarizing the evidence, we performed a risk of bias assessment to assess the certainty that there were no systematic factors that distorted the implicit-explicit comparisons in the included studies. This is imperative for reliable evaluation of results, as higher risk of bias leads to less reliable effect estimates, especially in light of recent reports of issues with bias in motor learning research in general.[96,97]

2. Methods

Prior to our search we registered our review on PROSPERO (International prospective register of systematic reviews; registration number CRD42016038249).

2.1. Criteria for inclusion of studies

2.1.1. Population

Studies that investigated healthy athletes/adults (>18 years of age) were included. Studies that included athletes with non-neurological sports-related injuries (e.g., ankle sprain, knee injury) were also eligible for selection.

2.1.2. Experimental design

Studies were included if they compared the effects of an implicit- with an explicit motor learning intervention on motor task performance in single- and dual-task (motor-motor or motor-cognitive) conditions on separate retention tests (i.e., after practice was terminated and the experimental interventions were no longer provided). Such tests are imperative to determine whether an intervention has any lasting effect on motor performance and automaticity. We distinguished between studies with immediate (<24h) and delayed (>24h) retention tests.[61,98] Published and non-published controlled trials for which a full report was available were eligible for inclusion.

2.1.3. Implicit and explicit motor learning interventions

Studies were included if they compared explicit and implicit motor learning interventions. This review followed the definitions outlined by a recent Delphi study,[47] which we also used in an earlier review on implicit motor learning post-stroke.[96] As such, implicit and explicit motor learning are thus not necessarily considered to be separate processes, but rather as two ends of a continuum, with purely implicit motor learning on one end (motor performance occurs without any processing of declarative movement related knowledge in working memory) and purely explicit motor learning on the other end (motor performance is completely dependent on the processing of declarative movement related knowledge in working memory). In sports practice, it will be difficult to induce pure implicit motor learning, as athletes will always have some awareness and verbal knowledge of their performance. Yet, interventions may lead to relatively more implicit learning when they actively minimize athletes' use of explicit declarative knowledge to improve their performance.

Hence, the following motor learning interventions were labeled as 'implicit': (1) Analogy learning: Providing the learner with a metaphorical instruction (e.g., for basketball free throws: "Shoot as if you are trying to put cookies into a cookie jar on a high shelf"[54]); (2) Errorless or error-reduced learning: Minimizing the chance of mistakes during practice (e.g., Initially practice golf putting at close range, and then gradually increase putting distance[48]);

(3) Dual-task learning: Performing an attention-demanding secondary task during practice (e.g., randomly generating letters while performing a table tennis forehand[55]); (4) External focus learning[57]: Focusing attention on movement effects/goals (e.g., for dart throwing: focusing on the flight of the dart or the bull's eye[99]).

In contrast, verbal explicit instructions (that describe how the participant should perform the movement), errorful learning/trial-and-error learning, and internal focus learning (where the learner is instructed to focus on movement execution itself) were considered to be 'explicit' motor learning strategies.[47] So-called "discovery learning" interventions were only included as an explicit intervention if learners were explicitly instructed to actively search rules of movement.

2.1.4. Types of motor tasks

Classical studies into implicit motor learning have focused on the sequencing processes underlying motor learning, by having participants learn a sequence of button presses (i.e., the serial-reaction time" (SRT) paradigm). Learning sports-related tasks, however, typically requires one to acquire and optimize the dynamics of movement rather than to master the appropriate sequence of movement.[95] Therefore, we only included studies in which participants needed to learn tasks with relatively complex movement dynamics (e.g., throwing, kicking, jumping, grasping, balancing, and the like), while excluding studies that merely focused on sequence (SRT) learning.[95] Also, since performing as good as possible is a key element in sports, we considered motor tasks to be sports-related only when such a performance optimizing criterion was given.

2.1.5. Outcome measures

In order to make a consistent comparison between learning interventions, we only focused on (dual-task) *performance* measures (e.g. seconds, meters, percentages, etc.). The degree of automaticity of movement was operationalized as motor dual-task performance after practice was completed. Two aspects of dual-task performance were assessed: (1) absolute motor performance in dual-task conditions and (2) the robustness of motor performance to dual-task interference (i.e., the relative difference in performance between single- and dual-task conditions, so-called motor dual-task costs).[14]

2.2. Data sources & search strategy

A medical research librarian assisted in the formulation of our search strategy (see Appendix 2.1). We did not impose any restrictions to our search. Two investigators (RP and EK) searched the following electronic databases, from their inception up till March 2nd 2017: MEDLINE (via Pubmed), CENTRAL, Embase, PsycINFO, SportDiscus and Web of Science. Unpublished reports, conference abstracts, ongoing studies and other grey literature were searched in BIOSIS Previews, British Library Inside, OpenGrey.eu, Clinical Trials.gov, The European Union Clinical Trials Register, ISRCTN registry, and the WHO International Clinical Trials Registry Platform.

2.3. Study selection

First, study eligibility was assessed based on title and abstract. Potential relevant reports were further assessed based on full text. The selection process was performed by two reviewers independently (RP and EK). In case of disagreement, reviewers sought consensus through discussion. A third independent reviewer (JK) was consulted in case of persistent disagreement.

2.4. Data extraction

Two reviewers (RP and EK) independently extracted data by means of a standardized data extraction form. We extracted information regarding design, methodology, demographics (e.g., age, gender, skill level, cognitive function tests); information regarding the experimental- and control intervention (e.g., type of motor learning intervention; frequency, volume, and duration of practice, retention test interval, type of dual-task); outcome measures and findings (estimates and measures of dispersion).

2.5. Risk of bias assessment

As stated earlier, for systematic reviews to obtain reliable conclusions, it is pertinent that potential limitations of the included studies are considered carefully. We used the Cochrane's risk of bias tool for this purpose.[100] Two reviewers (one with expertise in motor learning, EK, and one epidemiologist, MW) independently evaluated the 5 major domains of biases (see Cochrane for detailed information[100]):

- Selection bias: i.e., the presence of systematic differences between experimental groups in terms of possible confounding prognostic factors. This can be prevented by proper random allocation of participants to an experimental and control group, and by concealing the allocation from the persons involved in participant enrollment.
- Performance bias: i.e., the presence of systematic differences between groups in how interventions are administered, other than the differences between the experimental and control intervention. Think of more, longer, or more intense practice sessions for one group compared to the other, or of differences in exposure to other important factors (e.g., the person providing the intervention may implicitly have a more positive attitude towards and/or gives more attention to one group of participants than to the other. This can be prevented by blinding the participants and personnel providing the intervention to group allocation)
- Detection bias: i.e., a systematic difference in how the intervention's outcome is determined. This may especially influence subjective outcomes (e.g., the outcome assessors beliefs/hypotheses regarding the interventions of interest may implicitly make him/her more likely to award higher points to one group than to the other), but also plays a role

with objective outcomes (e.g., when the assessor (implicitly) has a more positive attitude toward one group of participants than to the other, this may systematically influence performance outcomes). Detection bias can be prevented by blinding the outcome assessor

- Attrition bias: i.e., the presence of systematic group differences in the number of persons that quit or drop-out from the experiment prematurely, or that are excluded from analyses. Attrition bias is low when a study accurately reports study flow, and there are no clear imbalances between groups in terms of drop-outs or exclusions.
- Reporting bias: i.e., the presence of differences between the reported (published) findings, and the initially planned and/or non-reported analyses. Low risk of reporting bias can be ascertained when a registered study protocol confirms that all analyses were carried out as planned, and all planned outcomes have been reported.
- Other bias: We additionally determined whether there were any other potential risk of biases, such as the absence of a separate pre-test to assess possible baseline differences in motor ability between groups

Two reviewers (one with expertise in motor learning, EK, and one clinical epidemiologist, MW) independently evaluated the included studies. Risk of bias on each domain was scored using a set of predefined criteria. In line with recommendations, we specifically modified these criteria for the purpose of this review (Appendix 2.2).[100,101] Individual items were scored '+' for low risk of bias; '-' for high risk of bias and '?' for unclear risk of bias. Eventually, controlled trials were classified as low risk of bias (all items: '+'), moderate risk of bias (1 or 2 items: '-'), or high risk of bias (>2 items: '-'). Trials were assigned an unclear risk of bias when 4 or more items were scored '?'.

We scored the corresponding overall 'Level of Evidence' in accordance to the table of Oxford's Centre for Evidence-Based Medicine.[102] In this system, level 1 evidence is assigned to systematic reviews. Randomized controlled trials at low risk of bias are classified as level 2 of evidence. Lastly, nonrandomized controlled trials are assigned a level 3 evidence. In case of an overall unclear or high risk of bias the strength of the evidence may be reduced by 1 level.[102]

2.6. Data synthesis and analysis

The analysis focused on both absolute dual-task performance and dual-task costs at retention. For absolute performance, we assessed performance of the primary, newly-learned motor skill and the secondary task during dual-task conditions. To determine dual-task costs, we calculated the percentage difference in performance between single-task (ST) and dual-task (DT) conditions at retention using the following formula: DT costs (DTC) = [(ST-DT)/ST*100]. Higher costs indicate a larger deterioration of performance in the DT condition compared to the ST condition. If possible, we also calculated DT costs for the secondary task. Secondly, we assessed the reported amount of declarative knowledge of the intervention- and control groups, to assess the degree to which the interventions induced explicit (and thus implicit) learning. If the implicit group had gained significantly less declarative knowledge than the explicit group, the manipulation was considered successful.[41,47,49,96]

By means of the risk of bias assessment we determined whether quantitative data synthesis through meta-analysis or subgroup analysis would be possible. Only low or moderate risk of bias studies are eligible for data synthesis.[100] If studies overall were at unclear or high risk of bias, we planned a descriptive synthesis. When data of interest was not specifically reported in the text, extraction of outcome values would be done, if necessary, manually (i.e., conversion from graphs using InkScape). Subsequently, we conducted an unpaired independent t-test if the exact relevant means and standard deviations could be obtained. If not, P-values for the comparisons of interest were extracted from the studies' text. Finally, a funnel plot was used to assess the possible presence of publication bias.

3. Results

3.1. Study selection

Figure 2.2 shows the flow of study selection. The search yielded a total of 4125 single hits. Screening for title and abstract resulted in the identification of 119 possibly relevant reports. However, a majority of these reports was excluded after full text screening because they did not make a comparison between implicit- and explicit learning interventions (N=37), or lacked dual-task assessment at retention (N=37). Nine other studies were excluded because they did not investigate a sports-relevant (motor) task. Three congress abstracts were identified that were possibly relevant. However, attempts to contact the primary investigators were unsuccessful.

Eventually, 25 studies were included in this systematic review (Figure 2.2).[48,50,54–56,72,74,75,87,103–118] Several studies described multiple experiments (N=4[48,56,110,113]), retention tests (i.e., both immediate and delayed retention tests; N=3[105,111,113]), or intervention groups (i.e. two implicit groups; N=6[48,55,72,104,111,118]). We evaluated these separately, such that our review includes a total of 39 implicit-explicit motor learning comparisons: 29 concern comparisons on immediate retention tests, and 10 concern comparisons on delayed retention tests. The possibility of publication bias was explored by means of a funnel plot (Appendix 2.3). Only half (N=19) the comparisons could be included in the funnel plot, as standard deviations were missing for the other studies. No evidence for publication bias was deemed present: The funnel plot appeared to have a symmetrical distribution, and Egger's[119] test revealed that the distribution was not statistically asymmetrical (B_0=-1.821,SE=1.192, 95% CI[-4.335, 0.693], p=0.145).

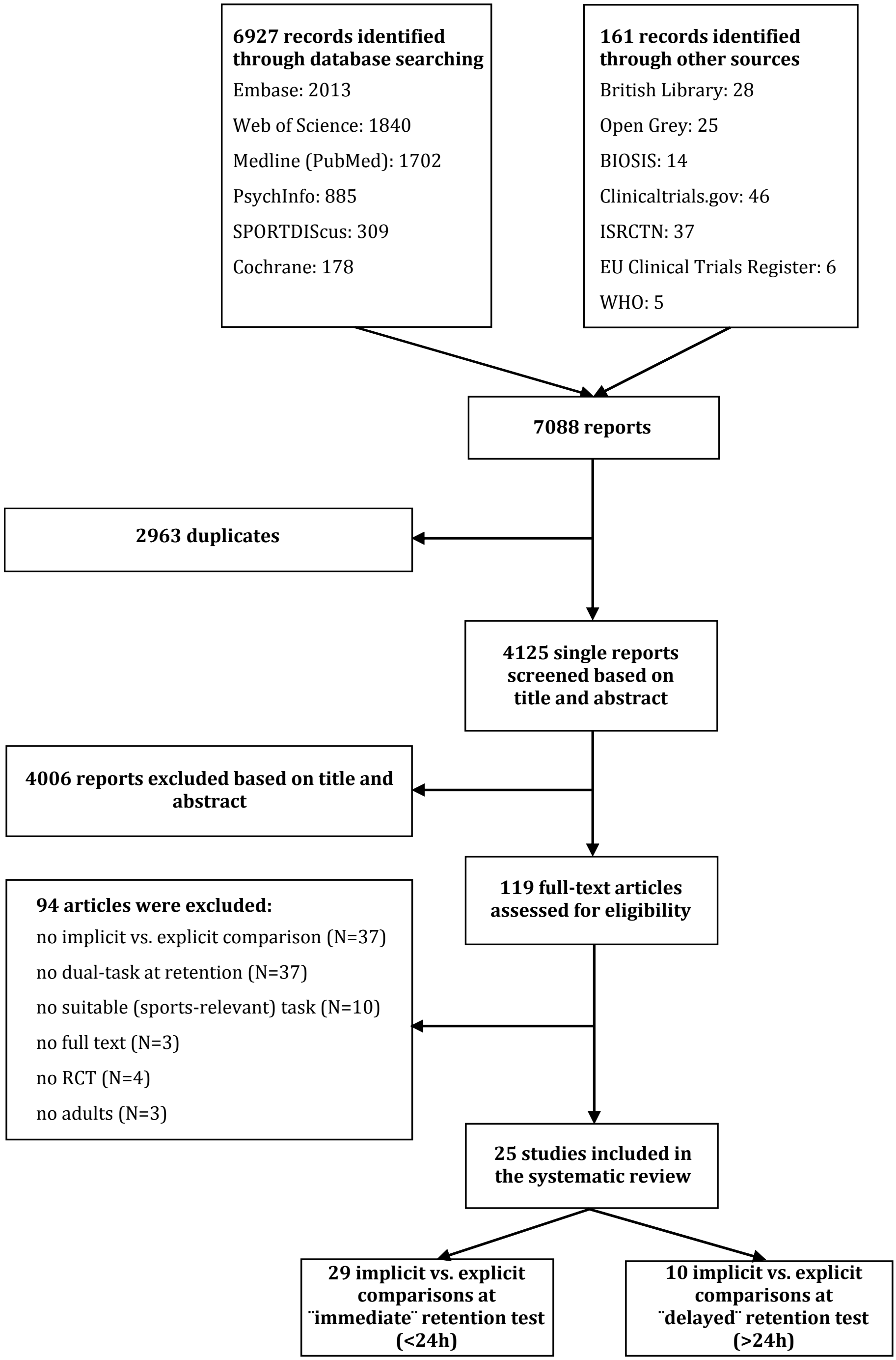


Figure 2.2. Flow chart of study search and selection.

3.2. Study characteristics

Appendix 2.4 provides a detailed overview of each study's characteristics. Twenty-five randomized controlled trials were included, totaling 1040 participants (41% men vs. 59% women). Most studies concerned young adults (mean age=26.50 years; range=18-67 years), who were novice with respect to the motor task they needed to learn: 20 of the 25 studies explicitly state that participants had no prior experience, 5 studies do not describe participants' experience. Overall the majority of studies involved small sample sizes (mean=13.9 participants per experimental group, range=6-25). Practice durations varied from 1 day to 6 weeks, while subsequent retention interval ranged from 5 minutes to 2 weeks. The types of motor tasks investigated included: golf tasks (N=6[48,50,56,72,114,115]), table tennis tasks (N=6[55,104,105,107,112,118]), balance board tasks (N=4[75,87,110,111]), basketball free throws (N=2[54,106]), rugby passing (N=2[74,109]), miscellaneous aiming/throwing tasks (N=3[103,113,116]), and a surgical task[108] and Pedalo riding[117] (both N=1). Dual-task assessments at retention mostly consisted of counting tasks; both backward counting (N=8[54,55,103–105,112,117,118]) and tone counting (N=6[48,50,56,72,110,113]) were frequently tested. Other studies used (variants of) probe reaction tasks (N=5[87,106,107,114,115]) or had participants generate random digits/letters or sequences thereof (N=6[74,75,108,109,111,116]).

3.3. Risk of bias assessment

The risk of bias assessment was performed separately for each experiment. In this section, we therefore refer to experiments, rather than studies.

Figure 2.3 provides an overview of biases per domain per experiment. Overall, experiments exhibited an unclear risk of bias. This was predominantly due to a significant lack of reporting. For instance, no detailed descriptions were available of randomization procedures[cf. 111] and blinding of researchers, participants and outcome assessor, nor were any study protocols available to assess reporting bias. Further, only 5 experiments reported on the number of drop-outs in the experiment.[74,75,109,111,114] Of these, 2 experiments[109,111] scored a high risk of so-called attrition bias, due to a drop-out rate of more than 10%. Generally, experiments scored best on one item of performance bias, namely the check the degree to which learning was indeed more implicit in the implicit learning group than in the explicit learning group. In 14 experiments the implicit group reported less explicit knowledge than the explicit group,[54–56,72,74,103–106,108,111,112,115,118] while this was not the case for 9 other experiments.[48,50,56,75,104,107,110] Seven experiments lacked this manipulation check, and therefore were scored as having an "unclear risk of bias" on this item.[87,109,113,114,116,117]

	Randomization	Group allocation	Blinding participants	Manipulation checks	Blinding outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Abdoli 2012	?	?	?	+	?	?	?	–
Chauvel 2012	?	?	?	+	?	?	?	–
Koedijker 2007 - analogy vs. explicit	?	?	?	+	?	?	?	–
Koedijker 2007 - external vs. internal focus	?	?	?	–	?	?	?	+
Koedijker 2008	?	?	?	+	?	?	?	+
Lam 2009a	?	?	?	+	?	?	?	–
Lam 2009b	?	?	?	+	?	?	?	–
Lam 2010	?	?	?	–	?	?	?	–
Liao 2001 - Experiment 1	?	?	?	+	?	?	?	–
Masters 2008a	?	?	?	+	?	?	?	–
Masters 2008b	?	?	?	?	?	–	?	–
Maxwell 2001 - Experiment 1	?	?	?	–	?	?	?	–
Maxwell 2001 - Experiment 2	?	?	?	–	?	?	?	–
Maxwell 2002 - Experiment 1	?	?	?	–	?	?	?	–
Maxwell 2002 - Experiment 2	?	?	?	–	?	?	?	–
Orrell 2006a	?	?	?	–	?	+	?	–
Orrell 2006b	–	?	?	+	?	–	?	–
Poolton 2005	?	?	?	–	?	?	?	–
Poolton 2006 - Experiment 1	?	?	?	+	?	?	?	–
Poolton 2006 - Experiment 2	?	?	?	–	?	?	?	–
Poolton 2007a	?	?	?	+	?	+	?	–
Poolton 2007b	?	?	?	+	?	?	?	–
Sanli 2014 - Experiment 1	?	?	?	?	?	?	?	–
Sanli 2014 - Experiment 2	?	?	?	?	?	?	?	–
Schucker 2010	?	?	?	?	?	+	?	+
Schucker 2013	?	?	?	+	?	?	?	–
Singer 1993	?	?	?	?	?	?	?	–
Totsika 2003	?	?	?	?	?	?	?	–
Tse 2017	?	?	?	+	?	?	?	–
Wulf 2001	?	?	?	?	?	?	?	–

Figure 2.3. Summary of risk of bias assessment per experiment. NB: '-' is high risk of bias; '+' = low risk of bias; '?' = unclear risk of bias

In the category other biases it was assessed whether groups were of similar motor skill before the intervention. For 3 experiments no differences in motor skill were evident on a pretest, and these were thus scored as having a low risk of bias on this domain.[104,105,114] All other studies were assigned a high risk of bias. With regard to the use of a pretest, we acknowledge that there is a good reason for researchers to not incorporate a pretest in their design. That is, during a (task-specific) pretest learners may already acquire explicit knowledge of the to-be-learned motor skill, which would interfere with subsequent implicit motor learning.[48] However, please note that the overall risk of bias assessment would be unaffected and remain "unclear", even if the absence of pretest assessments would not be taken into consideration. We refer to the discussion section for a more detailed discussion of this and the other risk of bias issues noted here.

Overall, all studies were generally found to be at unclear risk of bias. This meant that (1) the strength of the evidence was confined to level 3 (nonrandomized controlled trials); and (2) that descriptive data synthesis was performed, as data synthesis by means of meta-analysis was not justified.[29]

3.4. Descriptive synthesis

Table 2.1 gives an overview of the main intervention effects for all experiments and comparisons made. Based on retention interval, we made a distinction between immediate (<24h) and delayed (>24h) retention test phases. We categorized different comparisons of learning interventions to discuss our main outcome values: absolute (motor + cognitive) dual-task (DT) performance; (motor + cognitive) dual-task costs (DTC); declarative knowledge. In order to show strong evidence for superior DT performance due to implicit motor learning, we determined that the implicit group must demonstrate significantly better motor DT performance (i.e., better absolute motor DT performance or lower motor DTCs) *and* significantly less declarative knowledge compared to the explicit group.

Finally, where possible, we also report single-task (ST) results for each group comparison. This was done to check whether differences in motor skill level possibly confounded group comparisons in dual-task performance. For instance, less skilled ST motor performance may result in greater decrements in motor performance in DT conditions,[120] (see also Figure 2.1). We refer to the 'Results' column of Appendix 2.4 for details on the extracted data for each comparison.

Table 2.1. Summary of intervention effects for comparisons with immediate (<24 h) retention intervals.

Study/experiment	Comparison	Significant group differences (implicit vs explicit group)					
		Motor ST	Motor DT	Cognitive DT	Motor DTC	Cognitive DTC	Declarative knowledge
Chauvel et al. (2012) [72]	Errorless vs Errorful - Young	=	=	=	N/A	N/A	+
	Errorless vs Errorful - Old	=	=	=	N/A	N/A	+
Koedijker et al. (2007) [104]	Analogy vs Explicit	=	=	=	=	N/A	+
	External vs Internal	=	=	=	=	N/A	=
Koedijker et al. (2008) - *Test phase 1* [105]	Analogy vs Explicit	=	=	=	=	N/A	+
Lam et al. (2010) [107]	Errorless vs Errorful	=	=	=	=	N/A	=
Liao et al. (2001) - *Experiment 1* [55]	Analogy vs Explicit	?	?	N/A	+	N/A	+
	Dual-task vs Explicit	?	?	N/A	+	N/A	+
Masters et al. (2008a) [108]	Errorless vs Explicit	=	=	N/A	=	N/A	+
Masters et al. (2008b) [109]	Errorless vs Errorful	=	+	N/A	+	N/A	N/A
Maxwell et al. (2001) - *Experiment 1* [48]	Errorless vs Errorful	=	+	=	+	N/A	=
Maxwell et al. (2001) - *Experiment 2* [48]	Errorless vs Errorful	?	?	=	N/A	N/A	=
Maxwell et al. (2002) - *Experiment 1* [110]	External vs Internal	=	=	=	=	N/A	=
Maxwell et al. (2002) - *Experiment 2* [110]	External vs Internal	=	=	=	=	N/A	=
Orrell et al. (2006a) [111]	Errorless vs Explicit	=	=	N/A	=	N/A	=
Orrell et al. (2006b) - *Test phase 1* [75]	Analogy vs Explicit	-	-	N/A	=	N/A	+
	Errorless vs Explicit	=	=	N/A	=	N/A	+
Poolton et al. (2005) [50]	Errorless vs Errorful	?	?	=	+	N/A	=
Poolton et al. (2006) - *Experiment 1* [56]	External vs Internal	=	+	=	+	N/A	+
Poolton et al. (2006) - *Experiment 2* [56]	External vs Internal	=	=	=	=	N/A	=
Poolton et al. (2007a) [74]	Errorless vs Errorful	=	=	N/A	+	N/A	+
Poolton et al. (2007b) [112]	Analogy vs Explicit	?	?	N/A	+	N/A	+
Sanli et al. (2014) - *Experiment 1-Test Phase 1* [113]	Errorless vs Errorful	=	=	=	=	N/A	N/A
Sanli et al. (2014) - *Experiment 2-Test Phase 1* [113]	Errorless vs Errorful	=	=	=	=	N/A	N/A

Table 2.1. Continued

Schücker et al. (2010) [114]	Analogy vs Explicit	=	=	=	?	N/A	N/A
Schücker et al. (2013) [115]	Analogy vs Explicit	?	=	=	N/A	N/A	+
Singer et al (1993) [116]	External vs Internal	?	+	=	N/A	N/A	N/A
Tse et al (2017) [118]	Analogy vs Explicit – Young	+	+	N/A	=	N/A	+
	Analogy vs Explicit – Old	+	+	N/A	=	N/A	+

NB: Green '+': Significantly (p<0.05) better performance or less declarative knowledge for implicit group compared to explicit group; Yellow '-': Significantly (p<0.05) better performance or more declarative knowledge for explicit group compared to implicit group; '=': No significant difference between implicit and explicit groups; '?': Outcome measure was assessed, but corresponding p-values could not be obtained; N/A**:** Outcome measure not assessed. Abbreviations: DT= dual-task; DTC= dual-task costs.

Table 2.2. Summary of intervention effects for comparisons with delayed (>24 h) retention intervals.

Study/ Experiment	Comparison	Significant group differences (implicit vs explicit group)					
		Motor ST	Motor DT	Cognitive DT	Motor DTC	Cognitive DTC	Declarative knowledge
Abdoli et al. (2012) [103]	Errorless vs Errorful	+	+	=	+	N/A	+
Koedijker et al. (2008) - *Test phase 2* [105]	Analogy vs Explicit	=	=	=	=	N/A	+
Lam et al.(2009a) [106]	Analogy vs Explicit	=	=	=	=	N/A	+
Lam et al.(2009b) [54]	Analogy vs Explicit	=	+	=	+	N/A	+
Orrell et al. (2006b) - *Test phase 2* [75]	Analogy vs Explicit	-	-	=	?	N/A	+
	Errorless vs Explicit	=	=	=	?	N/A	+
Sanli et al. (2014) - *Experiment 1-Test Phase 2* [113]	Errorless vs Errorful	=	=	=	=	N/A	N/A
Sanli et al. (2014) - *Experiment 2-Test Phase 2* [113]	Errorless vs Errorful	=	=	=	=	N/A	N/A
Totsika et al. (2003) [117]	External vs Internal	+	+	N/A	?	N/A	N/A
Wulf et al. (2001) [87]	External vs Internal	+	+	+	=	+	N/A

NB: Green '+': Significantly ($p<0.05$) better performance or less declarative knowledge for implicit group compared to explicit group; Yellow '-': Significantly ($p<0.05$) better performance or more declarative knowledge for explicit group compared to implicit group; '=': No significant difference between implicit and explicit groups; '?': Outcome measure was assessed, but corresponding p-values could not be obtained; N/A**:** Outcome measure not assessed. Abbreviations: DT= dual-task; DTC= dual-task costs.

3.4.1. Immediate retention (<24h)

3.4.1.1. Errorless vs Errorful/Explicit instruction

First, we describe the results of the thirteen comparisons of errorless and errorfull/explicit motor learning interventions. These comparisons concerned the following motor tasks: golf-putting (N=5),[48,50,72] rugby-throwing (N=2),[74,109] disc-propelling (N=2),[113] a surgical task (N=1),[108] balancing (N=2),[75,111] and table tennis.[107] The DT assessments consisted of tone-counting (N=7),[48,50,72,113] probe reaction time(N=1),[107] random letter generation (N=3),[74,111] and digit sequence recall plus kettle lift (N=2).[75]

No single comparison showed significant differences in motor ST performance for the implicit (i.e., errorless) compared to the explicit group.

Two comparisons[48,109] found significantly better motor DT performance for the implicit group compared to the explicit group. Nine comparisons[72,74,75,107,108,111,113] did not show significant differences, whereas this measure could not be obtained for two other comparisons.[48,50] Cognitive DT performance did not differ for eight comparisons[48,50,72,107,113] whereas this measure was unavailable for the other five comparisons.[74,75,108,109,111] Four comparisons[48,50,74,109] revealed significantly lower motor DTC for the implicit group. Six comparisons[75,107,108,111,113] did not show significant differences, whereas no motor DTCs were available for other three comparisons.[48,72] No comparisons were available for cognitive DTCs.

Five comparisons[72,74,108,111] found significantly less declarative knowledge for the implicit group, five others[48,50,75,107] did not reveal any group differences, while the three others[109,113] did not assess this measure.

Combined, no comparison showed superior absolute motor DT performance paired with less declarative knowledge for the errorless group compared to the explicit group, while one comparison showed superior motor DTCs and less declarative knowledge for the errorless group compared to the explicit group.[74] Thus, there is little evidence that errorless learning benefits motor DT performance compared to explicit learning.

3.4.1.2. Analogy vs Explicit

Second, we included nine comparisons of analogy versus explicit motor learning interventions. These concerned the following motor tasks: table-tennis (N=6),[55,104,105,112,118] balancing (N=1),[111] and golf (N=2).[114,115] DT assessments included counting backwards (N=6),[55,104,105,112,118] digit sequence recall plus additional kettle lift (N=1),[111] or a tone-judgment task (N=2).[114,115]

With regard to single-task motor performance, group differences were evident for three comparisons. Tse et al. found significantly better ST performance for the implicit (i.e., analogy) groups (both young and old) than for the explicit groups,[118] while Orrell et al. reported opposite results.[111]

Tse et al.[118] found significantly better motor DT performance for the implicit groups than for the explicit groups, both in young and older adults. In contrast, Orrell et al.[111] found significantly better motor DT performance for the explicit- in comparison to the implicit group. Four comparisons[104,105,114,115] did not show significant differences, whereas this measure could not be obtained for two other comparisons.[55,112] In four comparisons[104,105,114,115] cognitive DT performance did not significantly differ, whereas for the other five[55,111,112,118] this measure was not assessed. Two comparisons[55,112] showed significantly lower motor DTC for the implicit group. Five comparisons[104,105,111,118] did not show significant differences, whereas this measure was not available for two other comparisons.[114,115] None of the experiments analyzed DTC for the cognitive task.

For eight comparisons[55,104,105,111,112,115,118] significantly less declarative knowledge was reported by the implicit group than by the explicit group. Schücker et al.[114] did not asses this measure.

Combined, two comparisons reported superior absolute motor DT performance combined with less declarative knowledge for the analogy group compared to the explicit group,[118] while one comparison found *inferior* absolute motor DTs and less declarative knowledge for the analogy group.[111] Two comparisons revealed superior motor DTCs and less declarative knowledge for the analogy compared to the explicit groups.[55,112] Thus, there is weak evidence that analogy learning benefits motor DT performance compared to explicit learning.

3.4.1.3. External vs Internal Focus

Third, we included six external versus internal focus comparisons. These concerned the following motor tasks: table-tennis (N=1),[104] balancing (N=2),[110] golf (N=2),[56] and ball throwing (N=1).[116] DT assessments ranged from counting backwards (N=1)[104] and tone-counting (N=4)[56,110] to digit sequence recall (N=1).[116]

No single comparison showed significant differences in ST motor performance for the implicit (i.e., external) compared to the explicit (i.e., internal) group.

Two comparisons[56,116] revealed significantly better motor DT performance for the implicit- in comparison to the explicit group. The remaining four comparisons did not show any group differences in motor DT performance.[56,104,110] Cognitive DT performance was similar across groups for all six comparisons. Poolton et al. (Experiment 1)[56] reported significantly lower motor DTC for the implicit group. Four comparisons[56,104,110] did not show significant differences, whereas Singer et al.[116] did not assess this measure. No comparisons were available for cognitive DTCs.

Poolton et al. (Experiment 1)[56] found significantly less declarative knowledge for the implicit group. For four comparisons, no significant differences were found between groups.[104,110] Singer et al.[116] did not assess this measure.

Taken together, one comparison[56] found that the external focus group showed superior absolute motor DT performance, superior motor DTCs, and reported less declarative knowledge compared to the explicit group. Thus, there is little evidence that external focus learning benefits motor DT performance compared to explicit learning.

3.4.1.4. Dual-task vs Explicit

The fourth comparison of interest was that of dual-task vs explicit motor learning interventions. Liao et al.[55] compared the effectiveness of these interventions on learning a table tennis task. The dual-task assessment consisted of counting backwards.

No absolute motor and cognitive single and dual-task performance measures could be obtained from the report. Significantly lower motor DTCs for the implicit group were reported. Cognitive DTCs were not reported. Liao et al.[55] also reported significantly less declarative knowledge for the implicit group.

Thus, this comparison found evidence for better motor DT performance with implicit learning: the dual-task group showed both superior motor DTCs as well as less declarative knowledge compared to the explicit group.

3.4.2. Delayed retention (>24h)

3.4.2.1. Errorless vs Errorful/Explicit instruction

First, we included four errorless vs errorful/explicit instruction comparisons. These concerned the following motor tasks: disc-propelling (N=2),[113] ball-throwing (N=1),[103] and balancing (N=1).[111] DT assessments consisted of tone-counting (N=2),[113] counting backwards (N=1),[103] and tone-counting while kettle-lifting (N=1).[111]

Abdoli et al.[103] reported significantly better ST motor performance for the implicit (i.e., errorless) than for the explicit group. The other three comparisons did not show any differences in single-task performance.[111,113]

Abdoli et al.[103] reported significantly better motor DT performance for the implicit group. The three other comparisons[111,113] did not reveal any group differences in motor DT performance. Implicit and explicit groups showed similar cognitive DT performance in all four comparisons. Abdoli et al.[103] reported significantly lower motor DTC for the implicit group. Two comparisons[113] did not show significant group differences in motor DTC, while motor DTCs were unavailable for one comparison.[111] Cognitive DTCs were lacking for all four comparisons.

Two comparisons[103,111] found significantly less declarative knowledge for the implicit- than for the explicit group. No information was available for the other two comparisons, because Sanli et al.[113] did not assess learners' declarative knowledge.

Combined, out of the 4 comparisons, only Abdoli et al.,[103] reported superior absolute motor DT performance, motor DTCs, and less declarative knowledge for the errorless compared to the explicit group. There thus seems to be some evidence for better motor DT performance with errorless learning.

<u>3.4.2.2. Analogy vs Explicit</u>

Second, we included four comparisons of analogy and explicit motor learning. These concerned the following motor tasks: basketball-throwing (N=2),[54,106] table-tennis (N=1),[105] and balancing (N=1).[111] DT assessment consisted of counting backwards (N=2),[54,105] probe reaction time (N=1),[106] and tone counting while kettle-lifting (N=1).[111]

Orrell et al.[111] reported worse ST motor performance for the implicit (i.e., analogy) group than for the explicit group. The other three comparisons did not find differences in ST motor performance.[54,105,106]

Lam et al.[54] found significantly better motor DT performance for the implicit group. Orrell et al.,[111] on the other hand, demonstrated significant better motor DT performance for the explicit group. The two remaining comparisons[105,106] did not show significant group differences in motor DT performance. None of the comparisons revealed significant differences in cognitive DT performance. Lam et al.[54] reported significantly lower motor DTC for the implicit group. Two comparisons[105,106] did not reveal significant differences, whereas this measure was unavailable for one other comparison.[111] Cognitive DTCs were lacking for all four comparisons.

All comparisons revealed significantly less declarative knowledge for the implicit group.

Combined, one comparison[54] reported superior absolute motor DT performance, superior motor DTCs, and less declarative knowledge for the analogy group compared to the explicit group, while one comparison[111] found inferior absolute motor DT performance, similar motor DTCs, and less declarative knowledge for the analogy group. Therefore, there is conflicting evidence that analogy learning benefits motor DT performance compared to explicit learning.

3.4.2.3. External vs Internal

Finally, we included two comparisons of external versus internal focus interventions. One of these involved 'Pedalo' riding (N=1)[117] whereas the other involved learning of a balance board task (N=1).[87] The DT assessments were counting backward (N=1)[117] and a probe reaction time task (N=1).[87]

Both comparisons revealed[87,117] significantly better ST motor performance for the implicit- (i.e., external) than for the explicit (i.e., internal) group.

For both comparisons[87,117] significantly better motor DT performance was evident for the implicit group. Moreover, Wulf et al.[87] also showed a significantly better cognitive DT performance for the implicit group. This measure could not be obtained from Totsika et al.[117] Wulf et al.[87] reported no significant differences in motor DTC, but did find lower cognitive DTC for the implicit group. Totsika et al.[117] did not assess motor and cognitive DTCs.

Both Wulf and Totsika did not assess[87,117] learners' declarative knowledge.

Combined, there are clear indications for superior motor DT performance for the external focus groups than for the explicit groups. However, because declarative knowledge was not assessed, it is unclear whether this superior DT performance could be attributed to implicit motor learning.

4. Discussion

This systematic review assessed whether greater automatization of movement (or conversely, reduced reliance on conscious control) is achieved after implicit motor learning compared to explicit motor learning. This should be evidenced by implicit learning interventions resulting in superior absolute motor DT performance and/or lower motor DTCs, and less declarative knowledge compared to explicit interventions.

4.1. Main findings

In total, we included 25 controlled trials that described 39 implicit-explicit motor learning comparisons. In the majority of comparisons there were no group differences in absolute motor DT performance or motor DTCs. In 5 comparisons did the implicit group show superior absolute motor DT performance and less declarative knowledge compared to the explicit group.[54,56,103,118] In 7 comparisons lower DTCs and less declarative knowledge were found for the implicit group than for the explicit group.[54–56,74,103,112] Only in three comparisons did the implicit group show both significantly superior absolute DT performance *and* superior motor DTCs compared to the explicit group.[54,56,103] Opposite results were virtually absent, except for two comparisons which showed inferior absolute motor DT performance for the implicit group compared the explicit group.[111] No comparisons revealed better motor DTCs for the explicit group.

Those comparisons that found beneficial effects of implicit learning on motor DT performance involved different types of interventions – errorless learning,[74,103] dual-task learning,[55] analogy learning,[54,55,112,118] and external focus learning.[56] Also, these comparisons involved both immediate[55,56,109,112,118] and delayed[54,103] retention intervals. Thus, there are no strong indications that the effects of implicit motor learning on dual-task performance are influenced by the type of implicit intervention used, nor by retention interval. Yet, when we look at those comparisons for which ST motor performance results were also available, a trend is observed that ST and DT motor performance were correlated. That is, three of the six comparisons that showed better motor DT performance for implicit groups, also reported better ST motor performance[103,118] (with the other three not showing any ST differences[54,56,74]). Also, both comparisons that showed better DT performance for the explicit group also found better ST performance after explicit learning.[111] This raises the possibility that group differences in motor DT performance could in part be attributable to group differences in skill level per se, rather than the type of motor learning intervention (cf. Fig 1).

In sum, the majority of comparisons did not show differences in dual-task performance measures between implicit and explicit motor learning interventions. For the remaining comparisons there was a tendency toward better DT performance with implicit motor learning compared to explicit motor learning. As all studies scored an overall unclear risk of bias, the strength of the evidence is level 3. Below, we will first discuss how minimizing the risk of bias and more detailed reporting can strengthen motor learning research. We close with the implications for research and sports practice.

4.2. Minimizing risk of bias and strengthening research practices

The Cochrane risk of bias tool indicated an unclear risk of bias across the included studies, mostly due to underreporting of results. It thus seems that the expectations about reporting (and design) of authors, researchers, reviewers and editors in the field did not accord to the criteria used in the Cochrane risk of bias tool. To start with, we want to make absolutely clear that this must not be interpreted as an attack on the integrity of authors of the included studies, nor as evidence that the included studies were of poor quality. Also, we suspect that these findings are not specific to the studies in this review; earlier reviews revealed similar issues regarding underreporting and risk of bias issues in motor learning research in general.[96,97] Yet, the fact that we cannot establish the extent to which biases were *actually* present, or whether they affected the outcomes of the studies is precisely the main problem: It is impossible to tell whether the results summarized in this review are an accurate estimate of the underlying "true" effect, or whether they over- or underestimate it.[97] We therefore agree with Lohse et al.[97] that if the field of motor learning is to remain relevant, research and especially reporting practices need to be strengthened. Hence, the remainder of this section aims to increase awareness of the importance of detailed reporting and minimizing the risk of bias, and develop initial proposals to yield stronger levels of evidence. The risk of bias assessment performed in this review provides clear leads for this. These will be discussed in turn.

4.2.1. Reporting bias

The main issue noted in this review is a serious lack of reporting. Therefore, first and foremost future studies should use the CONSORT[121] and STROBE[122] statements to ensure that researchers comprehensively describe their methods and results. In addition, study protocols should be registered in advance to improve transparency and prevent possible reporting bias. We acknowledge that up till now limited options were available to pre-register non-medical research. Currently though suitable alternatives are widely available, either in the form of open-access repositories such as the Open Science Framework (https://cos.io/our-products/open-science-framework) or Dataverse (https://dataverse.org/), or in the form of so-called "registered reports" format that is increasingly adopted by scientific journals, in which the study protocol is pre-registered and peer-reviewed before the experiment is conducted.[123,124] For more clinically oriented studies the 'US National Institutes of Health Trial Register' and 'European Clinical Trial Register' are respected platforms for registration.

4.2.2. Selection, detection and performance bias.

Other necessary methodological improvements to minimize the risk of selection, detection, and performance bias include a detailed assessment of participants' baseline and background characteristics, proper blinding of personnel, and a manipulation check to ascertain the extent to which the experimental interventions indeed resulted in relatively more implicit/explicit motor learning.

First, participants' baseline and background characteristics should be described in detail, to ascertain sufficient group comparability. Most importantly, participants should be tested before commencement of the intervention to assess whether the investigated groups are similar in terms of motor ability. It has been argued that such a baseline assessment test should not involve the exact same motor task as during the training- and test phase, because learners would already acquire explicit knowledge of the to-be-learned motor skill, and hence be less able to learn implicitly. In fact, this is why many researchers purposely have discarded the use of pretest assessments in implicit motor learning research.[48] One way to avoid this might be to have participants perform a baseline assessment on a different, presumably related motor task (e.g., measure participants' sway during upright standing as baseline-test for stabilometer practice). This is only a preliminary suggestions of how baseline assessments may be done, whilst trying to prevent that subsequent implicit learning is thwarted. Future research is needed to test this approach, or to find alternative, possibly more suitable ideas to address this problem.

Second, with regard to blinding, future studies should strive to have independent and blinded researchers perform the group allocation and outcome assessment. This minimizes the possibility that the experimenter will be (subconsciously) influenced while performing allocation and pre- and post (retention)-tests. Blinding of the person who administers the intervention will be more difficult to achieve, if not impossible. One way to minimize such performance bias could be to appoint a research assistant with sufficient experimental skills (e.g., in the domains of biomechanics, physiology, social psychology), but who does not have in-depth knowledge of motor learning theories and is not aware of the research question and expected results. However, this will only partly reduce the performance bias risk; it cannot be ruled out that with time this person will figure out the hypothesis under investigation.

Third, studies must always include a manipulation check, in the form of an assessment of learners' declarative movement-related knowledge after practice is terminated. It is preferable if such assessments also probe a learner's episodic knowledge and not only the accumulated generic knowledge, as the former is more closely linked to the degree to which people explicitly control their performance.[125] A clear strength of the current literature is that most studies already incorporate episodic knowledge assessments,[48,50,54–56,72,75,103–112,118] Future studies could also screen episodic knowledge reports for hypothesis testing statements, which may be particularly indicative of explicit learning.[e.g., 48]

The above described suggestions illustrate how the robustness of research practices in the field of motor learning may be improved. They complement recommendations made by Lohse and co-workers[97] who additionally highlighted statistical biases in motor learning research. Combined, these suggestions may be suitable starting points for a so-called Delphi study in which motor learning experts along with statistical and methodological experts try to find consensus on standard protocols and reporting guidelines for different types of motor learning research.

4.3. Implications for research

There is some evidence that implicit motor learning improves movement automatization compared to explicit motor learning, but there is obviously a need to further strengthen the level of evidence. Based on our findings, analogy learning interventions may be best suited for further research, as it seemed most apt at inducing implicit motor learning. When we only consider the comparisons for which participants' declarative knowledge reports were available, analogy learning interventions most consistently effectuated implicit motor learning. Specifically, analogy groups reported less declarative knowledge than the explicit groups in all 12 comparisons that performed such checks.[54,55,104–106,111,112,115,118] In contrast, comparisons that concerned errorless learning (7 out of 12 comparisons[72,74,103,108,111]) were considerably less successful in this regard. Results are unclear for external focus interventions; one comparison revealed less explicit knowledge for the implicit group,[56] two did not,[56,110] while declarative knowledge checks were unavailable for the remaining 5 comparisons.[87,104,116,117] Dual-task learning successfully induced implicit motor learning in the one experiment that we included[55] (see also Masters[41]).

Relatedly, retention intervals influenced whether interventions successfully elicited implicit- and explicit motor learning. Manipulation checks were more often positive for comparisons that concerned a delayed retention test (N=6/6) than for comparisons that concerned immediate retention tests (N=15/24). Thus, a sharper distinction between implicit- and explicit learning interventions may be achieved when the retention tests are delayed by at least one night's sleep. This would be in line with findings that sleep results in better consolidation of both declarative and procedural knowledge,[e.g. 126] which may enhance the contrast between these knowledge types. Since the variety in used retention intervals could possibly affect the studies' outcome, one should strive to a fixed retention interval of more than 24 hours.[61,98]

Also, we recommend that studies not only compare explicit and implicit groups' motor DT performance, but also compare the extent to which performance deteriorates in DT compared to ST conditions – for instance by calculating DT costs.[14] In addition, the calculation of (cognitive) DT costs of the secondary task is required when examining the degree of movement automaticity. This could only be obtained from one[87] of the reviewed studies. Without cognitive DTC assessment it is impossible to say whether group differences in the primary motor DT performance and motor DTCs are not simply due to group differences in task prioritization during dual-tasking. Relatedly, it is important that researcher use task priority instructions and report these.

Further research may also validate potentially more objective methods than DT performance to assess the degree of movement automaticity. A promising addition is the use of EEG measurements. Zhu and co-workers found that increased movement automaticity is characterized by reduced coherence between left-sided verbal-analytical brain regions (T3-electrode) and central premotor brain regions (Fz).[68,127] In addition to this, there is evidence that task-irrelevant probes elicit less distinct event-related potentials (e.g., reduced amplitude of the P3 component observed at the Pz electrode) when the motor task is more automatic.[128]

Future research should also strive for longer practice periods. The majority of studies in this review only involved a single practice session.[48,50,55,56,72,74,75,104,107–113,115,117,118] As such, most of the evidence concerns the very early stages of learning, but relatively little is known about the long-term effects of implicit and explicit motor learning interventions (see Koedijker et al.,[105] Schücker et al.,[114] and Maxwell et al.[49] for noteworthy exceptions). There is good chance that differences in single- and dual-task motor performance become smaller with increased practice duration, given that – with sufficient practice – explicit learning should also lead to similar degrees of automaticity.[105] A sufficiently long practice period would allow researchers to compare movement automaticity between implicit and explicit groups at the end-stage, but also intermediate stages of skill development. This allows more fine-grained assessment of the degree to which implicit motor learning enhances movement automatization at different learning phases and/or skill levels.

Finally, future studies should incorporate larger samples, based on appropriate power calculations. Most studies in this review concerned relatively small groups (mean N=14 per experimental group). If studies lack sufficient power they are less likely to find significant effects. Also, when they do find an effect it is more likely to over- or understate the "true" effect.[97,129]

4.4. Implications for practice

For sports practice, there is currently not sufficiently strong evidence for the superiority of implicit interventions over explicit ones – at least not when it comes to improving automaticity (and dual-tasking). Please note that we did not assess other possible benefits of implicit motor learning to athletic performance (i.e., greater single-task performance increase, more resilient performance in fatiguing and high-stress conditions), so it is certainly possible that implicit motor learning benefits performance in other ways. For now, it may therefore be best for coaches and trainers to incorporate both approaches in their practice regimes, sometimes encouraging their athletes to use a more explicit approach and sometimes stimulating them to learn relatively implicitly. Based on this review, analogy learning may be one of the most promising implicit learning methods for practical application, although it certainly does require some ingenuity on the part of the coach to find proper individualized and meaningful analogies for each athlete for different tasks. There is currently no direct evidence that tells us in what circumstances it is best to either opt for an implicit or explicit approach. Some have hypothesized that explicit learning is best suited for improving (strategic) action selection (i.e., which movement solution is best for the given situation), whereas implicit strategies may be more suitable to refine the actual implementation of the movement. Also, it has been postulated that explicit approaches are useful when athletes want to improve or refine a firmly consolidated yet "attenuated" motor skill, or when they are confronted with novel, complex situations.[130] Coaches may also want to take into account their athletes' preferences and working memory; people with explicit motor control preferences and larger working memory capacity may benefit more from explicit interventions, and vice versa.[73,131] Still, please note that these are but hypotheses that await verification, and can by no means be used as fixed guidelines.

4.5. Strengths and limitations

We used a highly sensitive search strategy that was formulated by a research librarian and motor learning expert, and that encompassed numerous conventional electronic databases, grey literature sources, trial registers and hand searching of reference lists of included studies. Another strength is that all steps in the review process were performed by two independent reviewers. In addition, an epidemiologist and motor learning expert independently thoroughly assessed studies' risk of bias by means of the reference standard, the Cochrane's risk of bias tool. Nonetheless, several limitations remain.

First, this review was specifically restricted to the question of whether implicit motor learning leads to a greater degree of automatization of sports-related motor tasks compared to explicit motor learning. By doing so, we only focused on dual-task performance. Although single-task performance was assessed as well, this was only done for those studies that also looked at DT performance. Therefore, the fact that a few studies showed a benefit of implicit learning over explicit learning for single-task performance may be taken as indicative for the larger number of studies available on this topic, they are by no means definitive. Also, this review did not look into other presumed benefits of implicit motor learning, such as more robust performance under psychological and physiological stress.[e.g., 41] However, as these benefits are assumed to be associated with implicit motor learning resulting in accelerated movement automation, it was deemed to be most important to first scrutinize this latter proposition.

A second limitation is that for this review we relied on learners' self-reported declarative knowledge to verify whether the explicit group indeed learned more explicitly than the implicit group. There is debate regarding the validity of this approach, as it is unclear whether the rules reported post-learning are also actually used during practice, and whether their use actually gave rise to the observed performance improvements. Also, this measure may not be particularly sensitive to detect group differences.[132] Still, despite their limitations, verbal reports are currently the best available and most frequently used measures, that can best be compared across studies.

A third limitation is the absence of data synthesis by means of meta-analysis. Such an analysis allows to weigh studies according to their relative sample sizes and/or the precision of the effect estimate, and would therefore have provided more detailed insight into the relative effectiveness of implicit and explicit motor learning. However, the unclear risk of bias compromised the validity of meta-analysis, and required us to limit ourselves to a descriptive data synthesis.[100]

Fourth, the review was limited to four types of implicit motor learning interventions, namely analogy learning, errorless learning, dual-task learning, and external focus learning. This approach resulted in the exclusion of several other used interventions, such as discovery learning, which narrows the scope of this review. Also, while experts and practitioners generally agreed upon the former three interventions to be implicit motor learning interventions,[47] they did not label external focus learning as such. Nonetheless, this intervention was incorporated in this review, because there are indications that external focus learning is a relatively implicit form of learning,[86] that is suggested to result in a reduced build-up of declarative knowledge.[56,57]

Finally, the presence of publication bias was assessed by means of a funnel plot. However, not all comparisons could be included, due to missing standard deviations for certain comparisons. Hence, the possibility of publication bias cannot be completely excluded.

5. Conclusions

This study found level 3 evidence for a small positive effect of implicit motor learning on movement automaticity when compared with explicit motor learning. There is a clear need to further investigate the possible benefits of implicit motor learning for sports practice. This calls for uniform, motor learning-specific guidelines on design and reporting, to enable low-risk-of-bias trials that yield stronger evidence.

6. Acknowledgements

We would like to thank Ralph de Vries of the medical library of the Vrije Universiteit Amsterdam for his help with optimizing our search strategy.

Appendix 2.1. Search strategy

Example of the search strategy for Medline.

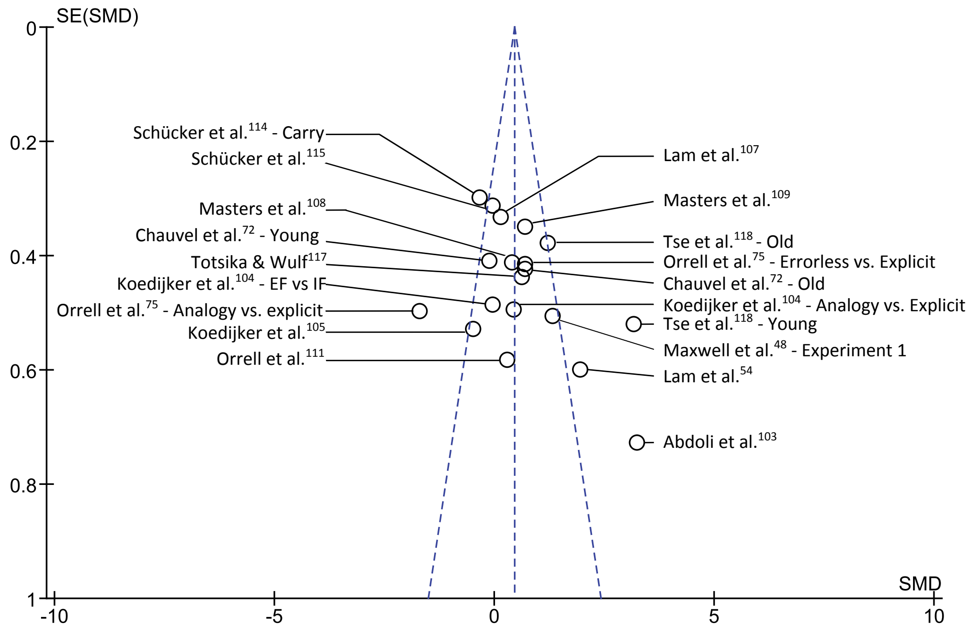
#1	"Learning"[Mesh] OR Learn*[tiab] OR memor*[tiab] OR knowledge[tiab]
#2	Implicit*[tiab] OR procedural*[tiab] OR unintentional*[tiab] OR incidental*[tiab] OR nondeclarative[tiab] OR non declarative[tiab] OR analogy[tiab] OR analogies[tiab] OR errorless[tiab] OR dual task[tiab] OR external*[tiab] OR observational*[tiab] OR unconscious*[tiab] OR Explicit*[tiab] OR internal*[tiab] OR reinvestment*[tiab] OR discover*[tiab] OR trial and error*[tiab] OR declarative*[tiab] OR conscious*[tiab]
#3	"Psychomotor Performance"[Mesh] OR "Motor skills"[Mesh] OR psychomotor*[tiab] OR task perform*[tiab] OR motor*[tiab] OR movement*[tiab] OR muscle control*[tiab] OR muscular control*[tiab]
#4	"Sports"[Mesh] OR sport[tiab] OR sports[tiab] OR distract*[tiab] OR multi task*[tiab] OR ((dual[tiab] OR secondar*[tiab] OR concurrent*[tiab]) AND task*[tiab]) OR (cognitive*[tiab] AND demand*[tiab]) OR (attention*[tiab] AND demand*[tiab])
#5	(#1 AND #2 AND #3 AND #4) NOT ("Animals"[Mesh] NOT "Humans"[Mesh])

Appendix 2.2. Cochrane Risk of Bias Tool

Domain of bias	Qualification	Criteria for assigning risk of bias
Selection bias		Sequence generation
	+	Computer based random number generators, a table with random numbers or similar methods
	-	Quasi randomization procedures e.g. allocation based on date of birth or on day of the week
	?	None described sequence generation
Selection bias		Allocation concealment
	+	Person(s) responsible for randomization should be independent and blinded to participant at randomization
	-	Person(s) responsible for randomization should are not independent or blinded to participant at randomization
	?	None described allocation concealment
Performance bias (1)		Blinding of participants and personnel
	+	Blinded participants and personnel; *It is stated that participants were not specifically informed about the nature of the intervention* *Personnel that provided intervention was not informed about nature of the intervention*
	-	Non blinded participants and personnel; *It is not stated that participants were not specifically informed about the nature of the intervention* *Personnel that provided intervention was not informed about nature of the intervention*
	?	None described or unclear blinding of participants and personnel
Performance bias (2)		Manipulation check of degree to which motor learning had been implicit/explicit
	+	Implicit group demonstrated significantly less movement-related knowledge than explicit group after learning
	-	No clear differences in movement-related knowledge between implicit and explicit groups
	?	No manipulation checks described/reported
Detection bias		Blinding of outcome assessment
	+	Blinded outcome assessor
	-	Non blinded outcome assessment
	?	Methods of (blinding) the outcome assessment were not described
Attrition bias		Incomplete outcome data
	+	Random lost to follow up of participants was present when ≤ 10% was lost to follow up
	-	Selective lost to follow up of participants was present when > 10% was lost to follow up
	?	Unclear lost to follow up
Reporting bias		*Selective reporting* (www.controlled-trials.com, ClinicalTrials.gov, http://apps.who.int/trialsearch/ were searched for protocols)
	+	Articles that reported all a priori described outcomes
	-	Articles that did not report all a priori described outcomes

	?	The protocol was not found.
Other biases		
	+	No other systematic errors were present
	-	Any other systematic errors that could lead to bias (e.g., baseline differences between groups in motor skill, or other possibly relevant factors)

Appendix 2.3. Funnel plot of included studies



NB: Only comparisons for which standard deviations were available could be included in the funnel plot. Assessment was conducted on the difference in absolute motor dual-task performance (X-axis) between implicit and explicit groups at the latest retention test; experiments with positive value on X-axis indicate better dual-task performance for the implicit group, in contrast to negative values which suggest explicit superiority. Only participants in Orrell et al.[75,111] executed a secondary motor task. These results were not included in this funnel plot. Some experiments consisted of more than one test phase[75,105,113] or motor outcome.[114] Therefore, multiple funnel plots were conducted to inspect whether this affected the result, but this was not the case. Abbreviations: EF = external focus; IF = internal focus; SMD = standardized mean difference; SE = standard error;

Appendix 2.4. Study Characteristics.

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Abdoli et al.[103]	**Number at baseline:** 30 **Inclusion/exclusion criteria:** No visual/motor impairment **Number of groups: 3** Errorless (n=10) Errorful (n=10) Control (n=10) **General descriptives:** Gender (m/f): 0/30 Age (years): 22±2.0 All participants were right handed **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Ball-throwing task - Hitting a concentric target on a board by bouncing the ball via a specific target zone on the ground - Maximum score: 10 points/throw	Groups of interest: Errorless ('Implicit'): Distance from target was progressively increased (2.5-3.5 m in 0.25 m steps). Errorful ('Explicit'): Distance from target was progressively reduced (3.5-2.5 m in 0.25 m steps); **Procedure:** *Days 1-3: Learning phase:* 5 blocks 25 ST trials / day End of day 3: 1 block of 10 ST trials at 3 m distance Day 4:Test Phase: 2 test blocks of 10 trials, at 3 m distance: ST DT (counting backwards from 1100 in steps of 3) 2 transfer tests (throwing from shorter/ longer distance than 3 m)	Primary outcome: Primary motor task: Throwing precision (number of points awarded per block; M± SD) Secondary task: Counting accuracy & speed (M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 49.4±4.5 DT = 46.3±5.3 DTC= 6.3% Explicit ST = 41.9±5.3 DT = 31.2±3.4 DTC = 25.5% **Secondary task performance:** *Implicit* ST = N/A DT Accuracy = 87±77% Speed = 13.68±2.97 DTC = N/A Explicit ST = N/A DT Accuracy = 66±13% Speed = 10.99±5.63 DTC = N/A **Declarative knowledge:** *Implicit* = 5.1±1.0 *Explicit* = 9.4±1.8 **Implicit versus Explicit comparison:** Motor ST: p=.003 Motor DT: p<.0001 Motor DTC: p<.05 Secondary DT: Accuracy: p=.41 Speed: p=.20 Secondary DTC: N/A Declarative knowledge: p<.0001

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Chauvel et al.[72]	**Number at baseline:** 48 younger adults 48 older adults Inclusion/exclusion criteria: No visual/hearing impairments No history of neurological disease No medication that affects cognition. **Number of groups: 4** Errorful-young (n=24) Errorless-young (n=24) Errorful-old (n=24) Errorless-old (n=24) **General descriptives:** Younger adults Gender (m/f): 24/24 Age (years): 23.5±3.3 Older adults Gender (m/f): 25/23 Age (years): 65.0±3.7 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	Groups of interest: Errorless ('Implicit'): Distance from target was progressively increased (0.25-1.0 m in 0.25 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (2.25-1.5 m in 0.25 m steps) **Procedure:** *Day 1: Learning phase:* 4 blocks of 40 ST trials. Day 1: Test phase: One 40 trial-block, at 1.25 m distance Groups were split: ST: ½ of errorless & errorful groups DT: ½ of errorless & errorful groups (secondary tone counting while putting)	Primary outcome: Primary motor task: Number of successful putts (M±SD) Secondary task: Counting accuracy (%; M±SD) Secondary outcome: Declarative knowledge: Number of explicit hypothesis (M±SD)	**Motor task performance:** *Implicit-young* ST = 29.1±7.0 DT = 26.9±5.0 DTC = N/A Explicit-young ST = 29.1±3.0 DT = 27.5±4.3 DTC = N/A Implicit-old ST = 24.1±10.7 DT = 26.5±7.0 DTC = N/A Explicit-old ST = 24.0±6.7 DT = 21.5±6.7 DTC = N/A **Secondary task performance:** Implicit-young ST = N/A DT = 87.5±14.1% DTC = N/A Explicit-young ST = N/A DT = 89.2±8.8% DTC = N/A Implicit-old ST = N/A DT = 85.7±9.2% DTC = N/A Explicit-old ST = N/A DT = 78.6±9.9% DTC = N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
					Declarative knowledge: *Implicit – young&old combined:* 1.2 ± 0.9 *Explicit – young&old combined:* 1.6 ± 1.0 **Implicit versus Explicit comparison:** *Young groups* Motor ST: *p*=1.0 Motor DT: *p*=.76 Motor DTC: N/A Secondary DT: *p*=.73 Secondary DTC: N/A Old groups Motor ST: *p*=.96 Motor DT: *p*=.09 Motor DTC: N/A Secondary DT: *p*=.08 Secondary DTC: N/A Combined groups: Declarative knowledge: *p*=.042
Koedijker et al.[104] *- **Analogy vs. Explicit***	**Number at baseline:** 17 **Inclusion/exclusion criteria:** No experience in table tennis. Number of groups: 2 Explicit (n=9) Analogy (n=8) **General descriptives** *(of total sample – combined with Koedijker et al., 2007 – External vs. Internal focus):* Gender (m/f): 7/27 Age (years): 21.8±3.6	Table tennis task - Participants stood opposite a ball machine and hit the ball to target at opposite side of table	**Groups of interest:** Analogy ('Implicit'): "Pretend drawing a right-angled triangle with the bat" Explicit ('Explicit'): Explicit instructions on table tennis forehand performance **Procedure** *Day 1: Pretest:* 50 ST trials Day 1: Learning phase 9 blocks of 50 ST trials Day 1: Test phase: 3 test blocks of 50 trials: Low-pressure ST (LPT-ST) High-pressure ST (HPT-ST) Low-pressure DT (counting backwards from 1100 in steps of 3)	***Primary outcome*:** Primary motor task: Combined score of accuracy and movement execution (M± SD) Secondary task: Counting accuracy (%) and speed (s; M± SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal and external focus) rules (M± SD)	**Motor task performance:** *Implicit* (LPT-)ST = 2.88±1.21 DT = 3.09±1.66 DTC= -7.3% Explicit (LPT-)ST = 3.23±0.87 DT = 2.43±1.18 DTC= 24.8% **Secondary task performance:** *Both groups combined:* ST = N/A DT = Accuracy: 96-98% Speed: 2.46-2.87 s **Declarative knowledge:** *Implicit*: 4.0±1.8 *Explicit:* 7.6±2.8

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
	Specific group characteristics: N/A Pre-test single task motor performance: Explicit = 1.63±0.59 Analogy = 1.08±0.45 T-test on pretest: p=.049				**Implicit versus Explicit comparison:** Motor ST: p=.50 Motor DT: p=.37 Motor DTC: p>.05 Secondary DT: Accuracy: p>.05 Speed: p>.05 Secondary DTCs: N/A Declarative knowledge: p=.007
Koedijker et al.[104] – ***External vs. Internal Focus***	**Number at baseline:** 17 **Inclusion/exclusion criteria:** Same as described above (Koedijker et al. 2007 – Analogy vs. Explicit Learning) Number of groups: 2 External Focus (n=9) Internal Focus (n=8) **General descriptives:** Same as described above (Koedijker et al. 2007 – Analogy vs. Explicit Learning) **Specific group characteristics:** N/A **Pre-test single task motor performance:** External = 1.49±0.76 Internal = 1.66±1.00 T-test on pretest: p=.70	Table tennis task - Same as for Koedijker et al. 2007 – Analogy vs. Explicit Learning	Groups of interest: External focus ('Implicit'): "Attend to the ball at all times" Internal focus ('Explicit'): "Focus on movement execution" **Procedure** Identical to Koedijker et al. 2007 – Analogy vs. Explicit Learning	***Primary outcome:*** Primary motor task: Combined score of accuracy and movement execution (M±SD) Secondary task: Counting accuracy (%) and speed (s; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal and external focus) rules (M±SD)	**Motor task performance:** *Implicit* (LPT-)ST = 2.53±1.01 DT = 2.18±0.92 DTC= 13.8% Explicit (LPT-)ST = 2.60±1.00 DT = 2.22±1.01 DTC= 14.6% **Secondary task performance:** *Both groups combined:* ST = N/A DT = Accuracy: 96-98% Speed: 2.46-2.87 s **Declarative knowledge:** *Implicit*: 6.5±3.1 *Explicit:* 4.9±2.0 **Implicit versus Explicit comparison:** Motor ST: p=.89 Motor DT: p=.93 Motor DTC: p>.05 Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: p=.23

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Koedijker et al.[105]	**Number at baseline:** 15 **Inclusion/exclusion criteria:** No experience in table tennis **Number of groups: 2** Analogy (*n*=7) Explicit (*n*=8) **General descriptives:** Gender (m/f): 2/13 Age (years): 19.6±3.4 **Specific group characteristics:** N/A **Pre-test single task motor performance:** Analogy = 1.94±1.48 Explicit = 1.33±0.73 T-test on pretest: *p*=.32	Table tennis task - Participants stood opposite a ball machine and hit the ball to target at opposite side of table	**Groups of interest:** Analogy ('Implicit'): "Pretend drawing a right-angled triangle with the bat" Explicit ('Explicit'): Explicit instructions on table tennis forehand performance **Procedure:** 6 sessions, spread over six weeks: *Week 1: Pretest (PT):* 50 ST trials Week 1: Early learning phase: 14 blocks of 100 ST trials Week 1: Test phase 1: 3 test blocks of 50 trials Low-pressure ST (LPT-ST) High-pressure ST (HPT-ST) DT (counting backwards from 1100 in steps of 3) *Weeks 2 -5: Prolonged learning phase:* - Sessions 2&3: 15 blocks of 100 trials - Sessions 4&5: 20 blocks of 100 trials *Week 6: Test phase 2:* - Procedure similar to test phase 1, except that there was no pretest.	***Primary outcome:*** Primary motor task: Combined score of accuracy and movement execution (M±SD) Secondary task: Number of incorrect counts, and number of counts/second (M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal and external focus) rules (M± SD)	**Motor task performance:** ***Test phase 1 (Immediate)*** Implicit (LPT-)ST = 4.67±2.35 DT = 4.47±2.31 DTC= 4.3% Explicit (LPT-)ST = 4.09±1.60 DT= 3.84±1.87 DTC= 6.1% ***Test phase 2 (Delayed)*** *Implicit* (LPT-)ST = 4.42±1.53 DT = 4.24±1.06 DTC= 4.1% Explicit (LPT-)ST = 5.56±0.95 DT= 4.84±1.21 DTC= 12.9% **Secondary task performance:** *Both groups and test phases combined:* ST = N/A DT = Accuracy: 2.8±2.5 incorrect Speed: 0.5/s

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
					Declarative knowledge: ***Test phase 1 (Immediate)*** *Implicit*: 2.9±1.7 *Explicit:* 7.5±2.4 ***Test phase 2 (Delayed)*** *Implicit*: 2.4±0.6 *Explicit:* 5.0±1.8 **Implicit versus Explicit comparison:** ***Test phase 1 (Immediate)*** Motor ST: p=.58 Motor DT: p=.57 Motor DTC: p>.31 Secondary DT: p>.39 Secondary DTC: N/A Declarative knowledge: p=.001 Test phase 2 (Delayed) Motor ST: p=.10 Motor DT: p=.33 Motor DTC: p>.31 Secondary DT: p>.39 Secondary DTC: N/A Declarative knowledge: p=.003

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Lam et al.[106]	**Number at baseline:** 24 **Inclusion/exclusion criteria:** Only female participants **Number of groups: 2** Analogy (n=12) Explicit (n=12) **Specific group characteristics:** Analogy: Gender (m/f): 0/12 Age (years): 21.9±1.7 Weight (kg): 53.8±9.7 Height (m): 1.61±0.04 Explicit: Gender (m/f): 0/12 Age (years): 21.1±1.2 Weight (kg): 53.9±6.5 Height (m): 1.63±0.04 **Pre-test single task motor performance: N/A** **Pre-test single task secondary task performance:** Analogy: 452.3±79.7 Explicit: 424.3±67.9	Basketball free throws - Shooting from a seated position into a standard basketball rim	**Groups of interest:** Analogy ('Implicit'): "Shoot as if you are trying to put cookies into a cookie jar on a high shelf." Explicit ('Explicit'): Eight instructions describing correct shooting technique Procedure: Day 1&2: Learning phase: 6 blocks of 40 trials All participants aimed to maximize their shooting performance while responding as quickly as possible to auditory probes Day 3:Test phase: 2 retention blocks of 40 trials; ad random trials were performed Without auditory probes With auditory probes presented before movement initiation With auditory probes presented during movement execution 1 transfer block (similar procedure as for retention, but in high-pressure conditions)	Primary outcome: Primary motor task: Accuracy (number of points per block; M± SD) Secondary task: Probe reaction time (ms; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance: ?** *Authors do not report motor performance for trials with and trials without probes for implicit and explicit groups separately* **Secondary task performance:** *Implicit* ST = N/A DT (execution)= 447.7 ms Explicit ST = N/A DT (execution)= 455.7 ms **Declarative knowledge:** *Implicit*= 1.9±1.3 *Explicit* = 6.2±2.2 **Implicit versus Explicit comparison:** Motor ST: p>.10 Motor DT: p>.10 Motor DTC: p>.05 Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: p<.0001

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Lam et al.[54]	**Number at baseline:** 27 **Inclusion/exclusion criteria:** No previous experience with basketball shooting **Number of groups: 3** Explicit (n=9) Analogy (n=9) Control (n=9) General descriptives: Gender (m/f): ? Age (years): 21.0±1.1 Weight (kg): 49.1±5.7 Height (m): 1.59±0.05 **Specific group characteristics: N/A** **Pre-test single task motor performance: N/A**	Basketball free throws - Shooting from a seated position into a standard basketball rim.	**Groups of interest:** Analogy ('Implicit'): "Shoot as if you are trying to put cookies into a cookie jar on a high shelf." Explicit ('Explicit'): 8 instructions describing correct shooting technique **Procedure:** *Day 1-3: Learning phase:* 8 blocks of 20 ST trials per day Day 4:Test phase: 3 test blocks of 20 trials: 2 ST blocks 1 DT blocks (counting aloud backward in threes from 1100)	Primary outcome: Primary motor task: Accuracy (number of points per block; M±SD) Secondary task: Counting accuracy (%) and speed (counts/minute; M±SD) Secondary outcome: Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 65.7±3.5 DT = 65.7±4.1 DTC= 0% Explicit ST = 65.8±5.1 DT = 59.3±1.6 DTC= 9.9% **Secondary task performance:** *Implicit* ST = N/A DT Accuracy= 91.9% Speed= 20.8 counts/min DTC = N/A Explicit ST = N/A DT Accuracy= 91.1% Speed= 21.1 counts/min DTC = N/A **Declarative knowledge:** *Implicit* = 2.7±0.8 *Explicit* = 7.9±2.2 **Implicit versus Explicit comparison:** Motor ST: p=.96 Motor DT: p<.001 Motor DTC: p<.05 Secondary DT: Accuracy= p>.05 Speed= p>.05 Secondary DTCs: ? Declarative knowledge: p<.0001

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Lam et al.[107]	**Number at baseline: 36** **Inclusion/exclusion criteria:** No experience with golf putting or field hockey **Number of groups:** 2 Errorless (n=18) Errorful (n=18) **General descriptives:** Gender (m/f): 22/14 Age (years): 21.5±2.0 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	Groups of interest: Errorless ('Implicit'): Distance from target was progressively increased (0.25-2.0 m in 0.25 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (2.0-0.25 m in 0.25 m steps) **Procedure:** *Day 1: Learning phase:* 8 blocks of 50 trials Ad random trials were performed Without auditory probes With auditory probes presented before movement initiation With auditory probes presented during movement execution Day 1: Test phase: 4 blocks of 50 trials, at 2 m distance: 2 blocks with similar procedure to practice blocks 2 transfer blocks: putting with unusual putters	Primary outcome: Motor task: Accuracy (number of points per block; M±SD) Secondary task: Probe reaction time (ms; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (mechanical+hypothesis testing) rules (M± SD)	**Motor task performance:** *Implicit* ST (no probe) = 101.1±38.6 DT (execution) = 94.9±37.0 DTC= 6.1% Explicit ST (no probe) = 88.6±38.5 DT (execution) = 88.8±35.4 DTC= 0.2% **Secondary task performance:** *Implicit* ST = N/A DT = 513.7±100.6 Explicit ST = N/A DT = 559.3±117.9 **Declarative knowledge:** *Implicit* = 4.3±2.2 *Explicit* = 4.2±2.2 **Implicit versus Explicit comparison:** Motor ST: p=.34 Motor DT: p=.73 Motor DTC: p>.12 Secondary DT: p=.39 Secondary DTC: N/A Declarative knowledge: p=1.0

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Liao et al.[55]	**Number at baseline: 30** **Inclusion/exclusion criteria:** Novice table tennis players Never received any form of instruction Never practiced more than once a fortnight **Number of groups:** 3 Analogy (n=10) Dual-task (n=10) Explicit (n=10) **General descriptives:** Gender (m/f): 6/24 Age (years): 27.5±4.4 **Specific group characteristics:** For each group, gender (m/f): 2/8 **Pre-test single task motor performance:** N/A	Table tennis task - Hit table tennis ball onto target area with topspin using forehand stroke	**Groups of interest:** Analogy ('Implicit'): "pretend to draw a right-angled triangle with the bat" Dual-task ('Implicit'): Performed concurrent secondary task (random letter generation) Explicit ('Explicit'): Received 12 basic instructions on how to hit topspin forehand **Procedure:** *Day 1: Learning phase:* 6 blocks of 50 trials Day 1: Test phase: 2 test blocks of 50 trials: ST DT (counting aloud backwards in threes from 1100)	Primary outcome: Primary motor task: Accuracy (number of points per block; M±SD) Secondary task: Performance not assessed ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit (analogy)* ST = 30.67 DT = 29.92 DTC= 2.4% Implicit (dual-task) ST = 28.01 DT = 27.46 DTC= 2.0% Explicit ST= 32.59 DT = 18.81 DTC= 42.3% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit (analogy)* = 1.51 *Implicit (dual-task)* = 0.97 *Explicit* = 6.54 **Implicit versus Explicit comparison:** Motor ST: ? Motor DT: ? Motor DTC: Analogy&Dual-Task groups vs. Explicit group: $p<.01$ Analogy vs. Dual-task group: $p=.97$ Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: Analogy&Dual-Task vs. Explicit group: $p<.001$ Analogy vs. Dual-task group: $p=.52$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Masters et al.[108]	**Number at baseline: 36** **Inclusion/exclusion criteria:** Right-handed No previous operative experience **Number of groups:** 3 Errorless (n=12) Explicit (n=12) Control (n=12) **General descriptives:** Gender (m/f): 17/19 Age (years): 22±3 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A_	Suturing and knot tying task	**Groups of interest:** Errorless ('Implicit'): The correct position of suture points were pre-marked to reduce mistakes Explicit ('Explicit'): Detailed verbal instructions about the task were provided concurrent with demonstration of skill **Procedure:** *Day 1: Learning phase:* 5 familiarization ST trials after observation of two different expert demonstrations of skill 50 ST practice trials Day 1: Test phase: 2 test blocks of 5 trials: ST DT (random letter generation)	Primary outcome: Primary motor task: Task completion time (seconds; M±SD) Secondary task: Performance not assessed ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 211.3±45.1 DT = 214.8±45.3 DTC= 1.7% Explicit ST = 202.2±37.8 DT = 238.1±62.8 DTC= 17.8% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit* = 2.8±1.8 *Explicit* = 5.3±3.4 **Implicit versus Explicit comparison:** Motor ST: p=.60 Motor DT: p=.31 Motor DTC: p=.12 Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: p=.03
Masters et al.[109]	**Number at baseline: 41 (6 drop-outs)** **Inclusion/exclusion criteria:** Not specified **Number of groups:** 2 Errorless (n=17) Errorful (n=18) General descriptives: Gender (m/f): ? Age (years): 20.5±1.2 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Rugby passing task - Rugby ball needed to be thrown underhand at an elevated target (125 cm) consisting of 3 concentric squares (30, 100 & 150 cm)	Groups of interest: Errorless ('Implicit'): Distance from target was progressively increased (1.0-3.0 m in 0.5 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (6.0-4.0 m in 0.5 m steps) **Procedure:** *Day 1: Learning phase:* 100 ST trials Day 1: Test phase: 4 test blocks of 10 trials, from 3.5 m distance: 2 ST 1 DT (random letter generation) 1 transfer block (10 ST trials after fatigued performance test on a treadmill)	Primary outcome: Primary motor task: Accuracy (millimeters from target; M±SD) Secondary task: Performance not assessed ***Secondary outcome:*** Declarative knowledge: No declarative knowledge assessment	**Motor task performance:** *Implicit* ST = 188.2±43.1 DT = 184.0±37.5 DTC= -2.2% Explicit ST = 171.6±47.7 DT = 211.2±39.0 DTC= 23.1% **Secondary task performance: N/A** **Declarative knowledge: N/A** **Implicit versus Explicit comparison:** Motor ST: p=.29 Motor DT: p=.04 Motor DTC: p<.05 Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Maxwell et al.[48] ***Experiment 1***	**Number at baseline: 29** Inclusion/exclusion criteria: No golfing experience **Number of groups:** 3 Errorless (n=11) Errorful (n=9) Control (n=9) General descriptives: Gender (m/f): ? Age (years): 20.9±2.4 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	**Groups of interest:** Errorless ('Implicit'): Distance from target was progressively increased (0.25-2.0 m in 0.25 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (2.0-0.25 m in 0.25 m steps) **Procedure:** *Day 1: Learning phase:* 8 blocks of 50 ST trials Day 1: Test phase: 3 blocks of 50 trials, from 2 m distance: 1 ST 1 DT (tone counting task) 1 transfer block from novel distance of 3 m	Primary outcome: Primary motor task: Number of successful puts (M±SD) Secondary task: Accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 41.4±6.6 DT = 41.6±6.7 DTC= -0.6% Explicit ST = 36.6±4.8 DT = 32.8±5.9 DTC= 10.3% **Secondary task performance:** *Implicit* ST = N/A DT = 93.3±8.8% Explicit ST = N/A DT = 94.9±6.9% **Declarative knowledge:** *Implicit*= 4.3±1.6 *Explicit* = 3.1±1.5 **Implicit versus Explicit comparison:** Motor ST: p=.086 Motor DT: p=.006 Motor DTC: p=.047 Secondary DT: p=.66 Secondary DTC: N/A Declarative knowledge: p=.10

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Maxwell et al.[48] ***Experiment 2***	**Number at baseline: 55** Inclusion/exclusion criteria: No previous golfing experience **Number of groups:** 4 Errorless experimental (n=14) Errorless control (n=13) Errorful experimental (n=14) Errorful control (n=14) General descriptives: Gender (m/f): ? Age (years): 21.0±2.8 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	Groups of interest: Errorless ('Implicit'): Distance from target was progressively increased (0.25-0.75 m in 0.25 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (1.75-1.25 m in 0.25 m steps) **Procedure:** *Day 1: Learning phase:* 3 blocks of 50 ST trials Day 1: Test phase: 1 block of 50 trials, from 1 m distance ST: errorless & errorful control groups DT (tone counting task): errorless & errorful experimental groups	Primary outcome: Primary motor task: Number of successful puts (M±SD) Secondary task: Accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules + hypotheses (M±SD)	**Motor task performance:** *Implicit* ST (errorless control) = 39.4 DT (errorless exp) = 34.4 DTC = N/A Explicit ST (errorful control) = 35.5 DT (errorful exp)= 30.6 DTC = N/A **Secondary task performance:** *Implicit* ST (errorless control) = N/A DT (errorless exp)= 95.2±5.4 DTC = N/A Explicit ST (errorful control) = N/A DT (errorful exp)= 95.3±4.9 DTC = N/A **Declarative knowledge:** *Implicit*: Errorless control = 3.2 Errorless exp = 4.1 Explicit Errorful control = 5.3 Errorful exp = 6.1 **Implicit versus Explicit comparison:** Motor ST: ? Motor DT: ? Motor DTC: N/A Secondary DT: p=.94 Secondary DTC: N/A Declarative knowledge (combined errorless vs combined errorful groups): p>.05

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Maxwell et al.[110] ***Experiment 1***	**Number at baseline: 20** Inclusion/exclusion criteria: No experience with surfing, windsurfing or skate boarding (i.e., skills similar to the wobble board task) **Number of groups:** 2 External focus (n=10) Internal focus (n=10) General descriptives: Gender (m/f): ? Age (years): 21.2±4.2 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Balancing task - Keeping a stabilometer (wobble board) horizontal	**Groups of interest:** External focus ('Implicit'): Augmented feedback of deviation of balance board (red dot) "Keep the board within the target circle" Internal focus ('Explicit'): Augmented feedback of deviation of their feet (same red dot) "Keep your feet within the target circle" **Procedure:** *Day 1: Learning phase:* Ten 90-second ST trials Day 1: Test phase: 2 blocks of three 90-second trials ST DT (tone counting task)	Primary outcome: Primary motor task: Time on target (seconds) (M± SD) Secondary task: Accuracy (%; M±SD) Secondary outcome: Declarative knowledge: Number of explicit (combined internal and external focus) rules (M±SD)	**Motor task performance:** *Implicit* ST = 85.84 DT = 86.85 DTC= -1.2% Explicit ST = 84.71 DT = 86.31 DTC= -1.9% **Secondary task performance:** *Implicit* ST = N/A DT = 94.64% Explicit ST = N/A DT = 91.54% **Declarative knowledge:** *Implicit*: 1.7 *Explicit*: 2.0 **Implicit versus Explicit comparison:** Motor ST: p>.05 Motor DT: p>.05 Motor DTC: p>.05 Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: p>.05

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Maxwell et al.[110] ***Experiment 2***	**Number at baseline: 20** Inclusion/exclusion criteria: No previous golfing experience **Number of groups:** 2 External focus (n=10) Internal focus (n=10) General descriptives: Gender (m/f): ? Age (years): 22.2±4.0 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Balancing task - Keeping a 2-axial stabilometer horizontal	**Groups of interest:** External focus ('Implicit'): "Keep the board horizontal" Internal focus ('Explicit'): "Keep your feet horizontal" **Procedure:** *Day 1: Learning phase:* Ten 90-second ST trials Day 1: Test phase: 2 blocks of three 90-second trials ST DT (tone counting task)	Primary outcome: Primary motor task: Pitch (RMSE backward-forward deviations; M±SD) Roll (RMSE medio-lateral deviations; M±SD) Secondary task: Accuracy (%; M± SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal and external focus) rules (M± SD)	**Motor task performance:** *Implicit* ST ('Pitch') = 18.0 DT ('Pitch') = 18.2 DTC ('Pitch') = 1.1% ST ('Roll') =18.4 DT ('Roll') =18.2 DTC('Roll') = -1.1% Explicit ST ('Pitch') = 20.1 DT ('Pitch') = 21.1 DTC ('Pitch') = 5.0% ST ('Roll') = 20.3 DT ('Roll') = 20.2 DTC('Roll') = -0.5% **Secondary task performance:** *Implicit* ST = N/A DT = 95.83% DTC = N/A Explicit ST = N/A DT = 94.14% DTC = N/A **Declarative knowledge:** *Implicit*: 2.1 *Explicit*: 1.8 **Implicit versus Explicit comparison:** Motor ST: p>.05 Motor DT: p>.05 Motor DTC: p>.05 Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: p>.05

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Orrell et al.[75]	**Number at baseline: 24 (2 drop-outs in stroke groups)** Inclusion/exclusion criteria: No neurological impairment **Number of groups:** 4 Errorless–stroke (n=5) Errorless–control (n=6) Discovery-stroke (n=5) Discovery–control (n=6) Specific group characteristics: Errorless-stroke Gender (m/f): 4/1 Age (years): 49.2±15.7 MMSE: 26.8±0.8 BBS: 38.4±5.8 Errorless-control: Gender (m/f): 3/3 Age (years): 67.2±8.7 MMSE: 29.2±0.7 BBS: 52.3±1.4 Discovery-stroke Gender (m/f): 5/0 Age (years): 54.6±12.2 MMSE: 25.8±1.3 BBS: 38.0±9.0 Discovery-control Gender (m/f): 3/3 Age (years): 63.2±5.3 MMSE: 29.3±0.8 BBS: 53.5±0.8 **Pre-test single task motor performance:** N/A	Balancing task - Keeping a 1-axial stabilometer horizontal	**Groups of interest:** Errorless-control ('Implicit'): Progressively reduced braking resistance (2.5kg-0kg in 0.5kg steps) Discovery-control ('Explicit'): Instruction to discover rules of how to perform the balancing task **Procedure:** *Day 1: Acquisition phase:* Twenty-four 60-second ST trials Day 1:Test phase 1: (no braking resistance) 4 ST-retention trials 2 ST-DT "Recall" trials 1st 30 seconds: ST 2nd 30 seconds: DT (recall random 6-digit sequences) 2 ST-DT "Kettle" trials 1st 30 seconds: ST 2nd 30 seconds: DT (reach out and pick up a 1-kg kettle with 1 hand) Day 7: Test phase 2:(no braking resistance) 2 ST trials	***Primary outcome:*** Primary motor task: RMSE of deviation from horizontal (M± SD) Secondary tasks: Performance not assessed ***Secondary outcome:*** Declarative knowledge: Number of explicit rules reported (M±SD)	**Motor task performance:** *Implicit* ST (1st 30 s of ST-DT trial) Recall = 6.09±0.23 Kettle = 5.79±0.25 DT (2nd 30 s of ST-DT trial) Recall = 6.25±0.36 Kettle = 6.08±0.27 DTC ('Recall') = 2.6% DTC ('Kettle') = 5.0% Explicit ST (1st 30 s of ST-DT trial) Recall = 6.35±0.43 Kettle = 5.96±0.42 DT (2nd 30 s of ST-DT trial) Recall = 6.37±0.38 Kettle = 5.81±0.33 DTC ('Recall') = 0.3% DTC ('Kettle') = -2.5% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit* = 1.8±0.8 *Explicit* = 2.7±1.0 **Implicit versus Explicit comparison:** Motor ST: Recall: p=.27 Kettle: p=.46 Motor DT: Recall: p=.59 Kettle: p=.15 Motor DTC Recall: p=>.05 Kettle: p=>.05 Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: p = 0.12

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Orrell et al.[111]	**Number at baseline: 42 (6 drop-outs)** Inclusion/exclusion criteria: No previous experience of surfing, snowboarding or other similar balancing tasks **Number of groups:** 3 Analogy (n=11) Errorless (n=13) Discovery (n=12) General descriptives: Gender (m/f): 17/19 Age (years): 20.3±1.2 Specific group characteristics: Analogy: Gender (m/f): 5/6 Errorless: Gender (m/f): 6/7 Discovery: Gender (m/f): 6/6 **Pre-test single task motor performance:** N/A	Balancing task - Keeping a 1-axial stabilometer horizontal	Groups of interest: Analogy ('Implicit'): "Pretend to be soldiers standing on guard outside Buckingham Palace" Errorless ('Implicit'): Amount of available displacement from horizontal axis was gradually increased every second trial Discovery learning ('Explicit'): Instructions to discover rules of how to perform the balancing task **Procedure:** *Day 1: Acquisition phase:* Sixteen 60-second ST trials Day 1: Test phase 1: 4 ST trials 2 ST-DT "Recall" trials 1st 30 seconds: ST 2nd 30 seconds: DT (recall random 7-digit sequence) 2 ST-DT "Kettle" trials 1st 30 seconds: ST 2nd 30 seconds: DT (reach out and pick up a 1-kg kettle with 1 hand) Day 15: Test phase 2: 2 ST trials 2 ST-DT trials "Count+Kettle" 1st 30 seconds: tone counting 2nd 30 seconds: tone counting + kettle-lifting task	***Primary outcome:*** Primary motor task: RMSE of deviation from horizontal (M±SD) Secondary task: Recall & Kettle: Performance not assessed Tone counting: Accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** ***Test phase 1 (Immediate)*** *Implicit* ST (1st 30 s of ST-DT trial) Analogy: Recall = 3.51±0.20 Kettle = 3.25±0.21 Errorless: Recall = 2.91±0.46 Kettle = 2.81±0.48 DT (2nd 30 s of ST-DT trial) Analogy: Recall = 3.26±0.26 Kettle = 3.55±0.20 Errorless: Recall = 2.77±0.49 Kettle = 2.94±0.50 DTC Analogy ('Recall') = -7.1% DTC Errorless ('Recall') = -4.8% DTC Analogy ('Kettle') = 9.2% DTC Errorless ('Kettle') = 4.6% Explicit ST (1st 30 s of ST-DT trial) Recall = 2.84±0.36 Kettle = 2.74±0.41 DT (2nd 30 s of ST-DT trial) Recall = 2.55±0.31 Kettle = 2.85 ±0.36 DTC ('Recall') = -10.2% DTC ('Kettle') = 4.0%

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
					Test phase 2 (Delayed) *Implicit* ST Analogy = 3.44±0.29 Errorless = 2.96±0.34 DT Analogy: Count = 3.59±0.28 Count+Kettle = 3.46±0.28 Errorless: Count = 2.59±0.43 Count+Kettle = 2.69±0.43 DTC Analogy ('Count') = 4.4% DTC Errorless ('Count')= -12.5% DTC Analogy ('Count+Kettle') = 0.6% DTC Errorless ('Count+Kettle') = -9.1% Explicit ST = 2.95±0.47 DT Count = 2.92±0.46 Count+Kettle = 2.44±0.45 DTC ('Count') = -1.0% DTC ('Count+Kettle') = -17.3% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit* Analogy = 1.6±1.1 Errorless = 2.1±1.0 *Explicit* = 2.8±0.8

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
					Implicit versus Explicit comparison: ***Test phase 1 (Immediate):*** Analogy vs Explicit Motor ST: Recall: p<.0001 Kettle: p=.0001 Motor DT: Recall: p<.0001 Kettle: p<.0001 Motor DTCs Recall: p=.84 Kettle: p=.81 Secondary DT: N/A Secondary DTC: N/A Errorless vs Explicit Motor ST: Recall: p=.68 Kettle: p=.70 Motor DT: Recall: p=.20 Kettle: p=.61 Motor DTCs Recall: p=.84 Kettle: p=.81 Secondary DT: N/A Secondary DTC: N/A ***Test phase 2 (Delayed):*** Analogy vs Explicit Motor ST: p=0.005 Motor DT: Counting: p<.001

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
					Counting+Kettle: $p<.0001$ Motor DTCs: ? Secondary DT (Counting): $p>.11$ Secondary DTC: N/A Errorless vs Explicit Motor ST: $p=0.95$ Motor DT: Counting: $p=.08$ Counting+Kettle: $p=.17$ Motor DTCs: ? Secondary DT (Counting): $p>.11$ Secondary DTC: N/A Test Phase 1+2: Declarative knowledge: Analogy vs Explicit: $p = .008$ Errorless vs Explicit: $p = .048$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Poolton et al.[50]	**Number at baseline: 35** Inclusion/exclusion criteria: No previous golf putting experience **Number of groups:** 2 Implicit-Explicit (n=17) Explicit (n=18) General descriptives: Gender (m/f): 11/24 Age (years): 21.1±1.5 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	Groups of interest: Implicit-Explicit ('Implicit'): Distance from target was progressively increased (0.25-2.0 m in 0.25 m steps); After fourth block of trials, a set of 6 putting technique instructions was provided Explicit: Distance from target was progressively increased (0.25-2.0 m in 0.25 m steps) Different from the implicit group, the 6 technical putting instructions were provided from start of learning **Procedure:** *Day 1: Learning phase:* 8 blocks of 50 trials (400 trials): Day 1: Test phase: 3 test blocks of 50 trials, all at 2 m 2 ST 1 DT (tone counting)	Primary outcome: Primary motor task: Number of successful putts (M±SD) Secondary task: Tone counting accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 28.23 DT = 31.11 DTC= -10.2% Explicit ST = 29.98 DT = 26.19 DTC=12.6% **Secondary task performance:** *Implicit* Single task = N/A Dual-task = 94.1% DTC = N/A Explicit Single task = N/A Dual-task = 92.8% DTC = N/A **Declarative knowledge:** *Implicit* = 4.1 *Explicit* = 5.2 **Implicit versus Explicit comparison:** Motor ST: ? Motor DT: ? Motor DTC: $p<.01$ Secondary DT: $p=.68$ Secondary DTC: N/A Declarative knowledge: $p>.05$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Poolton et al.[56]	**Number at baseline: 30** Inclusion/exclusion criteria: No experience with golf putting **Number of groups:** 2 Internal focus (n=15) External focus (n=15) General descriptives: Gender (m/f): 7/23 Age (years): 24.1±5.9 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task	**Groups of interest:** Internal focus ('Explicit'): "Direct attention to the swing of your hands" External focus ('Implicit'): "Focus on swing of the putter head" **Procedure:** *Day 1: Learning phase:* 10 blocks of 30 ST trials Day 1: Test phase: 3 blocks of 30 trials 2 ST 1 DT (tone counting)	Primary outcome: Primary motor task: Number of successful putts (M± SD) Secondary task: Tone counting accuracy (%; M± SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal/external) rules (M± SD)	**Motor task performance:** *Implicit* ST = 9.08 DT = 9.81 DTC= -8.0% Explicit ST = 9.44 DT = 7.30 DTC= 22.7% **Secondary task performance:** *Implicit* ST = N/A DT = 91.2% DTC = N/A Explicit ST = N/A DT = 93.3% DTC = N/A **Declarative knowledge:** *Implicit:* 4.0 *Explicit*: 5.3 **Implicit versus Explicit comparison:** Motor ST: p=0.54 Motor DT: p<.05 Motor DTC: p<.05 Secondary DT: p=.42 Secondary DTC: N/A Declarative knowledge: p<.05

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Poolton et al.[56]	**Number at baseline: 39** Inclusion/exclusion criteria: No experience with golf putting General descriptives: Gender (m/f): 15/24 Age (years): 20.4±3.8 **Number of groups:** 2; Internal focus (n=19) External focus (n=20) **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Golf putting task.	**Groups of interest:** Internal focus ('Explicit'): Received 6 instructions regarding desired movement of their hands External focus ('Implicit'): Received 6 instructions regarding desired movement of the club **Procedure:** Identical to experiment 1	***Primary outcome:*** Primary motor task: Number of successful putts (M±SD) Secondary task: Tone counting accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit (combined internal, external, and neutral) rules (M±SD)	**Motor task performance:** *Implicit* ST = 41.08 DT = 27.77 DTC= 32.4% Explicit ST = 41.83 DT = 35.11 DTC= 16.1% **Secondary task performance:** *Implicit* ST = N/A DT = 89.4 DTC = N/A Explicit ST = N/A DT = 88.4 DTC = N/A **Declarative knowledge:** *Implicit*: 5.5 *Explicit:* 4.8 **Implicit versus Explicit comparison:** Motor ST: p>.56 Motor DT: p>.56 Motor DTC: p=.42 Secondary DT: p=.81 Secondary DTC: N/A Declarative knowledge: p=.19

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Poolton et al.[74]	**Number at baseline: 56 (1 person excluded in errorful group)** Inclusion/exclusion criteria: No previous experience with rugby throwing task **Number of groups:** 2 Errorless (n=23) Errorful (n=22) Control (n=10) Specific group characteristics: Errorless & Errorful combined: Gender (m/f): 23/22 Age (years): 23.0±5.0 Control Gender (m/f) = 4/6 Age = 29.0±5.3 **Pre-test single task motor performance:** N/A_	Rugby throwing task - Rugby ball needed to be thrown underhand at an elevated target (125 cm) consisting of 3 concentric squares (30, 100, & 150 cm).	**Groups of interest:** Errorless ('Implicit'): Distance from target was progressively increased (1.0-3.0 m in 0.5 m steps) Errorful ('Explicit'): Distance from target was progressively reduced (6.0-4.0 m in 0.5 m steps) **Procedure:** *Day 1: Learning phase:* 10 blocks of 10 trials Day 1: Test phase: 4 test blocks of 10 trials, at 3.5 m: 2 ST 1 DT (random letter generation) 2 Transfer blocks (ST after fatigued-performance test) One year later: Test phase 2: 1 ST block (10 trials at 3.5 m)	Primary outcome: Primary motor task: Distance from target in mm (M±SD) Secondary task: Performance not assessed ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	Motor task performance: Implicit ST = 213.3 DT = 200.5 DTC= -6.0% Explicit ST = 189.7 DT = 240.4 DTC= 26.7% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit* = 2.4±1.8 *Explicit* = 4.5±2.9 **Implicit versus Explicit comparison:** Motor ST: $p>.05$ Motor DT: $p=0.06$ Motor DTC: $p<.01$ Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: $p<.005$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Poolton et al.[112]	**Number at baseline: 28** Inclusion/exclusion criteria: Not having received formal table tennis coaching or played table tennis more than once a month Cantonese as first language Right hand dominant **Number of groups:** 2 Analogy (n=14) Explicit (n=14) General descriptives: Gender (m/f): ? Age (years): ? **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A_	Table tennis task - Hit table tennis ball onto target area with topspin using forehand stroke	**Groups of interest:** Analogy ('Implicit'): "Move the bat as though it is traveling up the side of a mountain." Explicit: 6 technical table tennis forehand instructions **Procedure:** *Day 1: Learning phase:* 300 ST trials Day 1: Test phase: 3 test blocks 2 ST 1 DT (counting backwards)	Primary outcome: Primary motor task: Number of points scored (M±SD) Secondary task: Performance not assessed ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = 18.53 DT = 17.67 DTC= 4.6% Explicit ST = 19.27 DT = 13.76 DTC= 28.6% **Secondary task performance: N/A** **Declarative knowledge:** *Implicit* = 3.3 *Explicit* = 5.8 **Implicit versus Explicit comparison:** Motor ST: ? Motor DT: ? Motor DTC: $p<.05$ Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: $p<.001$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Sanli et al.[113] ***Experiment 1***	**Number at baseline: 19** Inclusion/exclusion criteria: Not specified **Number of groups:** 2 Errorless (n=10) Errorful (n=9) General descriptives: Gender (m/f): 10/9 Age (years) 25.6±3.2 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Aiming task - Subjects needed to propel small disc over a smooth table top, with the aim to stop it in a specified target circle	**Groups of interest:** Errorless ('Implicit'): Progressively reduced target size (i.e., 31-6.5 cm diameter, in 3.5 cm steps) Errorful ('Explicit'): Progressively increased target size (i.e., 6.5-31 cm diameter, in 3.5 cm steps) **Procedure:** *Day 1: Acquisition phase:* 200 trials (25 to each of eight target sizes) Day 1: Test phase 1: 2 test blocks of 25 trials, with 6.5 cm target size 1 ST 1 DT (tone counting) 1 Transfer test block of 25 trials, with a 4.5 cm target size that had not been practiced *Day 2: Test phase 2:* Identical to test phase 1.	***Primary outcome:*** Primary motor task: Proportion of errors (i.e., number of times the disc did not stop completely within the target area) (M±SD) Secondary task: Tone counting accuracy (%; M±SD) Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** ***Test phase 1 (Immediate)*** *Implicit* ST = 0.81 DT = 0.76 DTC= -6.2% Explicit ST = 0.82 DT = 0.75 DTC= -8.5% ***Test phase 2 (Delayed)*** *Implicit* ST = 0.83 DT = 0.81 DTC= -2.4% Explicit ST = 0.81 DT = 0.81 DTC= 0% **Secondary task performance:** ? **Declarative knowledge:** N/A **Implicit versus Explicit comparison (Test phase 1 & 2 combined):** Motor ST: p>.05 Motor DT: p>.05 Motor DTC: p>.05 Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Sanli et al.[113] ***Experiment 2***	**Number at baseline: 20** Inclusion/exclusion criteria: Not specified **Number of groups:** 2 Errorless (n=10) Errorful (n=10) General descriptives: Gender (m/f) = 8/12 Age (years) 21.2±2.9 **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Aiming task - Subjects needed to propel small disc over a smooth table top, with the aim to stop it in a specified target circle (6.5 cm diameter)	**Groups of interest:** Errorless ('Implicit'): Progressively increased distance from target (i.e., 3.5-7.5-11.5-15.5-18.5-22.5-26.5-30.5 cm distance) Errorful ('Explicit'): Progressively reduced distance from target (i.e., 30.5-26.5-22.5-18.5-15.5-11.5-7.5-3.5 cm distance) **Procedure:** Identical to Sanli 2014 – Experiment 1	***Primary outcome:*** Primary motor task: Proportion of errors (i.e., number of times the disc did not stop completely within the target area) (M±SD) Secondary task: Tone counting accuracy (%; M±SD) Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** ***Test phase 1 (Immediate)*** *Implicit* ST = 0.89 DT = 0.84 DTC = -5.6% Explicit ST = 0.88 DT = 0.82 DTC = -6.8% ***Test phase 2 (Delayed)*** *Implicit* ST = 0.95 DT = 0.89 DTC = -6.3% Explicit ST = 0.87 DT = 0.84 DTC = -3.4% **Secondary task performance:** ? **Declarative knowledge:** N/A **Implicit versus Explicit comparison (Test phase 1 & 2 combined):** Motor ST: $p>.05$ Motor DT: $p>.05$ Motor DTC: $p>.05$ Secondary DT: $p>.05$ Secondary DTC: N/A Declarative knowledge: N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Schücker et al.[114]	**Number at baseline:** 51 (5 drop outs) Inclusion/exclusion criteria: Inexperienced in golf playing and had no official permission to play golf in Germany **Number of groups:** 2 Analogy (n=25) Technical learning (n=21) General descriptives: Gender (m/f): 33/18 Age (years): 32.7±*12.3* Handedness (r/l): 49/2 **Specific group characteristics:** N/A **Pre-test single task motor performance:** Analogy Carry (m)=70.4±25.3 Off-line(°)=12.9±5.5 Technical learning Carry (m)=80.2±26.6 Off-line(°)=12.4±3.6 Between group pre-test comparison 'Carry': *p*=.21 'Off-line': *p*=.73	Full swing golf stroke	Groups of interest: Analogy ('Implicit'): 9 analogies on different aspects of position & 21 analogies on different aspects of swing; (e.g., "Imagine you have an open tube of toothpaste between your hands and the contents must not be pushed out" (grip)) Technical ('Explicit'): 9 technical instructions on position & 21 technical instructions on golf swing **Procedure:** *Week 1-6 Learning phase:* 1 golf lesson/week from golf-professional+1 hour free practice Test Phases: Pre (after 1st training):10 ST trials Post-ST (after 5th training): 10 ST trials Post-DT (after 6st training): Tone judgment task (judging in which phase of swing tone was played) 12 low-pressure DT trials 12 high-pressure DT trials	Primary outcome: Primary motor task: "Carry" distance (m; M±SD) "Off-line" flight deviance in degrees (M±SD) Secondary task: Tone judgement accuracy (%; M±SD) Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** *Implicit* ST Carry (m) = 81.7±*27.4* Off-line(°) = 12.2±5.0 DT (low pressure) Carry (m)=80.8±23.3 Off-line(°)=16.1±7.5 DTC ('Carry') = 1.1% DTC ('Off-line') = 32.0% Explicit ST Carry (m) = 90.2±*32.1* Off-line(°) = 12.9±5.7 DT (low pressure) Carry (m)=89.7±27.3 Off-line(°)=14.5±6.1 DTC ('Carry') = 0.6% DTC ('Off-line') = 12.4% **Secondary task performance:** *Implicit* ST = N/A DT (low pressure) = 27.0±13.9 DT = N/A Explicit ST = N/A DT (low pressure) = 27.6±11.7 DTC = N/A **Declarative knowledge:** N/A **Implicit versus Explicit comparison:** Motor ST Carry: *p*=.34 Off-line: *p*=.66 Motor DT Carry: *p*=.24 Off-line: *p*=.44 Motor DTC: *p*= ? Secondary DT: *p*=.88 Secondary DTC: N/A Declarative knowledge: N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Schücker et al.[115]	**Number at baseline: 41** Inclusion/exclusion criteria: No previous golf experience Never having received formal golf putting instructions **Number of groups:** 2 Analogy (n=20) Technical learning (n=21) **General descriptives:** Gender (m/f): 23/18 Age (years): 21.4±3.0 Handedness (r/l): 35/6 **Specific group characteristics:** Analogy: Gender (m/f): 11/9 Handedness (r/l): 17/3 Technical Gender (m/f): 12/9 Handedness (r/l): 18/3 **Pre-test single task motor performance:** N/A	Golf putting task	**Groups of interest:** Analogy ('Implicit'): "Perform the putt like a pendulum (with visual instruction of a weight swinging on a cord)" Technical ('Explicit'): A set of 6 technical putting instructions **Procedure:** *Day 1: Learning phase:* 6 blocks of 50 ST trials (300 trials total) Day 1: Test phase 4 blocks of 20 trials, all with DT (judging pitch of tone or movement phase when tone was played) 1 familiarization DT block 2 low pressure DT 1 high pressure DT	Primary outcome: Primary motor task: Mean distance from target (cm; M±SD) Secondary task: Tone pitch judgment accuracy (%; M±SD) Movement phase judgment accuracy (%; M±SD) ***Secondary outcome:*** Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit* ST = N/A DT = 28.2±6.8 DTC = N/A Explicit ST = N/A DT = 27.9±7.3 DTC =N/A **Secondary task performance:** *Implicit* ST = N/A DT Pitch: 93.3±11.2 Movement phase: 0.83±0.38 DTC = N/A Explicit ST = N/A DT Pitch: 92.8±12.1 Movement phase: 0.70±0.37 DTC = N/A **Declarative knowledge:** *Implicit* = 2.0±1.0 *Explicit* = 3.4±1.2 **Implicit versus Explicit comparison:** Motor ST: N/A Motor DT: p=.89 Motor DTC: N/A Secondary DT Pitch: p=.89 Movement phase: p=.27 Secondary DTC = N/A Declarative knowledge: p<.001

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Singer et al.[116]	**Number at baseline: 72** Inclusion/exclusion criteria: Not specified **Number of groups:** 4 Awareness group (n=18) Non-awareness (n=18) 5-Step Approach (n=18) Control (n=18) General descriptives: Gender (m/f): 36/36 Age (years): 20.1±? **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A	Non-dominant overhand throwing task - Subjects threw paddle balls via the ground at acircular target (diameter = 65.45 cm), from a 3.66 m distance	**Groups of interest:** Non-awareness ('Implicit'): Focus on one situational cue (e.g., center of the target) and to ignore movement information Awareness ('Explicit'): Instructions to be aware of the way that they threw the ball **Procedure:** *Days 1&2: Learning phase:* 5 blocks of 25 ST trials per day (250 in total) Day 2: Test phase 50 DT trials (Subjects learned a 5-digit sequence before throwing & needed to call out one of these digits when prompted during throwing)	Primary outcome: Primary motor task: Radial error (distance from target in degrees) (M±SD) Secondary task: Accuracy on digit recall task (%; M±SD) Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** *Implicit* ST = N/A DT = ? DTC = N/A Explicit ST = N/A DT = ? DTC = N/A **Secondary task performance: ?** **Declarative knowledge:** N/A **Implicit versus Explicit comparison:** Motor ST: N/A Motor DT: p<.05 Motor DTC: N/A Secondary DT: p>.05 Secondary DTC: N/A Declarative knowledge: N/A
Totsika et al.[117]	**Number at baseline: 22** Inclusion/exclusion criteria: No experience with Pedalo task **Number of groups:** 2 Internal focus (n=11) External focus (n=11) General descriptives: Gender(m/f): 10/12 Age (years): 23.4±? **Specific group characteristics:** Internal focus Gender (m/f): 5/6 External focus Gender (m/f): 5/6 **Pre-test single task motor performance:** N/A	Riding a Pedalo for 7 meters	**Groups of interest:** External focus ('Implicit'): "Focus on pushing the platforms forward" Internal focus ('Explicit'): "Focus on pushing your feet forward" **Procedure:** *Day 1: Learning phase:* 20 ST trials at preferred pace Day 2: Test phase 3 test blocks of 4 trials ST (riding forward as fast as possible) ST (riding backward as fast as possible) DT (riding forward as fast as possible + counting aloud backward in threes from two-digit number)	Primary outcome: Primary motor task: Movement time (s) (M±SD) Secondary task: Performance not assessed Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** *Implicit* ST = 11.5 DT = 15.8 DTC= 37.4% Explicit ST = 15.0 DT = 19.1 DTC= 27.3% **Secondary task performance:** N/A **Declarative knowledge:** N/A **Implicit versus Explicit comparison:** Motor ST: p<0.001 Motor DT: p<0.05 Motor DTC: ? Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: N/A

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Tse et al.[118]	**Number at baseline: 70** Inclusion/exclusion criteria: No experience with task Right-handed No neurological disease No (chronic) pain in back and right forearm, shoulder or hand **Number of groups:** 4 Analogy – Young (n=18) Explicit – Young (n=18) Analogy – Old (n=17) Explicit – Old (n=17) Specific group characteristics: Younger adults Gender (m/f): ? Age (years): 21.9±2.3 MMSE: >24 Digit span memory: 26±4.2 Older adults Gender (m/f): ? Age (years): 66.9±4.6 MMSE>24 Digit span memory: 20.0±5.4 **Pre-test single task motor performance:** N/A	Table tennis task - Hit table tennis ball onto target area with topspin using forehand stroke	**Groups of interest:** Analogy ('Implicit'): "Move your racket such that it is travelling up the side of a mountain" Explicit ('Explicit'): Received 9 basic instructions on how to hit topspin forehand **Procedure:** *Day 1: Learning phase:* 180 ST trials Day 1: Test phase 1 2 test blocks of 30 trials DT (counting backwards) ST Day 2: Test phase 2 1 test block of 30 trials ST	Primary outcome: Primary motor task: Accuracy (number of points per block; M±SD) Secondary task: Performance not assessed Secondary outcome: Declarative knowledge: Number of explicit rules (M±SD)	**Motor task performance:** *Implicit-young* ST = 54.4±5.1 DT = 44.5±5.3 DTC = 18.3% Explicit-young ST = 37.9±5.3 DT = 26.6±5.7 DTC = 30.0% Implicit-old ST = 31.3±7.6 DT = 25.0±7.3 DTC = 20.3% Explicit-old ST = 20.7±6.8 DT = 15.9±7.3 DTC = 23.4% **Secondary task performance:** N/A **Declarative knowledge:** *Implicit-young:* 3.8±1.2 *Explicit-young:* 9.2±2.7 *Implicit-old:* 4.4±1.3 *Explicit-old:* 7.4±2.1 **Implicit versus Explicit comparison:** *Young groups* Motor ST: $p<.001$ Motor DT: $p<.001$ Motor DTC: $p>.05$ Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: $p<.001$ Old groups Motor ST: $p<.001$ Motor DT: $p<.001$ Motor DTC: $p>.05$ Secondary DT: N/A Secondary DTC: N/A Declarative knowledge: $p<.001$

Study	Participants	Task	Intervention	Outcome measures	Results (retention)
Wulf et al.[87]	**Number at baseline: 28** Inclusion/exclusion criteria: No experience with task **Number of groups:** 2 Internal focus (n=14) External focus (n=14) General descriptives: Gender (m/f): 5/23 Age (years): ? **Specific group characteristics:** N/A **Pre-test single task motor performance:** N/A **Pre-test single task cognitive performance:** Internal focus: 360±? External focus: 349±?	Balancing task - Keeping a 1-axial stabilometer horizontal	**Groups of interest:** External focus ('Implicit'): "Focus on markers attached to the platform, and keep them horizontal" Internal focus ('Explicit'): "Focus on feet, and keep them horizontal" **Procedure:** *Day 1+2: Learning phase:* 7 trials of 90-seconds 6 DT (Probe reaction time task) 1 ST Day 3: Test phase: 7 trials of 90-seconds 6 DT (Probe reaction time task) 1 ST	Primary outcome: Primary motor task: RMSE deviation from horizontal (M±SD) Secondary task: Probe reaction time (ms; M±SD) Secondary outcome: Declarative knowledge: Not assessed	**Motor task performance:** *Implicit* ST = 3.5 DT = 3.3 DTC = -5.7% Explicit ST = 4.1 DT = 4.2 DTC = 2.4% **Secondary task performance:** *Implicit* ST = 295 DT = 301 DTC= 2.0% Explicit ST = 307 DT = 331 DTC= 7.8% **Declarative knowledge:** N/A **Implicit versus Explicit comparison:** Motor ST: *p*<.05 Motor DT: *p*<.05 Motor DTC: *p*>.05 Secondary DT: *p*<.01 Secondary DTC: *p*<.001 Declarative knowledge: N/A

NB: P<0.05: Significant difference between implicit- and explicit group; ?: Outcome measure was assessed, but exact values could not be obtained. N/A: Outcome measure not applicable from report. Abbreviations: BBS=Berg Balance Scale; DT= dual-task; DTC= dual-task costs; M=mean; MMSE=Mini-Mental State Examination; PRT=probe reaction time; RMSE=root-mean-square error; SD=standard deviation; ST=single-task;

Chapter 3

Is implicit motor learning preserved after stroke? A systematic review with meta-analysis

Elmar Kal
Marinus Winters
John van der Kamp
Han Houdijk
Erny Groet
Coen van Bennekom
Erik Scherder

PLoS One. 2016;11:e0166376

Abstract

Background: Many stroke patients experience difficulty with performing dual-tasks. A promising intervention to target this issue is implicit motor learning, as it should enhance patients' automaticity of movement. Yet, although it is often thought that implicit motor learning is preserved post-stroke, evidence for this claim has not been systematically analysed yet. Therefore, we systematically reviewed whether implicit motor learning is preserved post-stroke, and whether patients benefit more from implicit than from explicit motor learning.

Methods: We comprehensively searched conventional (MEDLINE, Cochrane, Embase, PEDro, PsycINFO) and grey literature databases (BIOSIS, Web of Science, OpenGrey, British Library, trial registries) for relevant reports. Two independent reviewers screened reports, extracted data, and performed a risk of bias assessment.

Results: Overall, we included 20 out of the 2177 identified reports, that allow for a succinct evaluation of implicit motor learning. Of these, only 1 study investigated learning on a relatively complex, whole-body (balance board) task. All 19 other studies concerned variants of the serial-reaction time paradigm, with most of these focusing on learning with the unaffected hand (N=13) rather than the affected hand or both hands (both: N=4). Four of the 20 studies compared explicit and implicit motor learning post-stroke. Meta-analyses suggest that patients with stroke can learn implicitly with their unaffected side (mean difference (MD) = 69 ms, 95% CI[45.1, 92.9], $p<.00001$), but not with their affected side (standardized MD = -.11, 95% CI[-.45, .25], $p=.56$). Finally, implicit motor learning seemed equally effective as explicit motor learning post-stroke (SMD = -.54, 95% CI[-1.37, .29], $p=.20$).

Conclusions: Overall, the high risk of bias, small samples, and limited clinical relevance of most studies make it impossible to draw reliable conclusions regarding the effect of implicit motor learning strategies post-stroke. High quality studies with larger samples are warranted to test implicit motor learning in clinically relevant contexts.

1. Introduction

Most people consider going out for a walk while conversing with a friend to be an enjoyable and relaxing activity. With a moderate pace and a pleasant conversation, the cognitive (talking) and motor (walking) tasks can normally be performed concurrently without much effort. For many patients with stroke, however, this is not the case, as they often find themselves struggling to perform such cognitive-motor dual-tasks. Although up to 80% of patients regains walking ability,[9] both gait[8] and postural control[10] often remain highly susceptible to interference from the concurrent performance of a cognitive task. This is not merely inconvenient, but actually compromises patients' mobility and safety. For example, the ability to maintain gait speed above 0.7 m/s is assumed necessary for safely crossing a street.[15] Yet, performing an additional cognitive task can reduce walking speed well below this value in people with stroke.[13,16] In addition, heightened dual-task interference also increases the risk of falling.[17] Significantly, however, current rehabilitation practice does not seem particularly effective at recuperating dual-task performance.[8]

Developing interventions to target dual-task interference requires knowledge of the aetiology of patients' dual-task impairment. In general, explanations revolve around the dual-task framework of Abernethy[19] and working memory (WM) model of Baddeley.[22] Basically, when dual-tasking, the "central executive" is considered responsible for dividing the available attentional resources between the two tasks. As long as there are sufficient attentional resources *and* the central executive appropriately allocates these resources, no interference occurs. After stroke, however, WM-capacity is often reduced. For instance, slowed information processing as well as executive function deficits are commonly observed.[27,133] These deficits limit patients' amount of attentional resources and their ability to appropriately allocate the resources between the tasks. In addition, many patients have difficulty with re-automating motor control, and use a highly cognitively-demanding strategy of consciously monitoring and controlling their movements.[28,134] As a result, motor tasks like walking may also place an increased *demand* on WM after stroke.

Based on the above, the two main ways to target dual-task interference post-stroke are (1) improving WM capacity and/or (2) reducing the WM demands associated with moving. Current evidence indicates that increasing WM-capacity is difficult, if not impossible.[135] An alternative approach is to reduce WM load by (re-)automating motor control as much as possible, preferably in the initial phase of motor rehabilitation after stroke. Admittedly, it is unlikely that all patients will eventually attain the same level of automaticity as they had before they suffered brain damage. Still, we argue that patients´ dual-tasking performance could already benefit from motor learning interventions that do result in some improvement in automaticity of movement. One intervention that seems especially fit for this purpose is implicit motor learning. In the current paper, we will systematically review evidence to determine whether this mode of motor learning is actually preserved in people with stroke. First though, we will shortly introduce the concept of implicit motor learning, and explain why it might be a promising intervention to improve motor functioning and dual-tasking post-stroke.

1.1. Different routes to movement automaticity after stroke: Explicit and implicit motor learning

Traditional views on skill acquisition[45,46] hold that in the early 'verbal-cognitive' phase of motor learning, motor control requires considerable WM involvement; novices accrue and employ declarative movement-related rules and strategies to consciously control motor performance. In the course of learning, however, motor control becomes progressively less dependent on declarative knowledge and instead increasingly relies on procedural knowledge that directly links task-relevant information to the desired motor response.[45] Since procedural knowledge does not require conscious processing, motor control becomes less dependent on working memory contributions. After extensive practice, finally, the 'automatic phase' is reached, in which motor control has become fully procedural. This view on motor learning – involving a shift from declarative toward procedural control of movement – is typically called *explicit* motor learning[41] (see Figure 3.1). Specifically, according to consensus among experts explicit motor learning is: "… learning which generates verbal knowledge of movement performance (e.g. facts and rules), involves cognitive stages within the learning process and is dependent on working memory involvement".[47(p.5)]

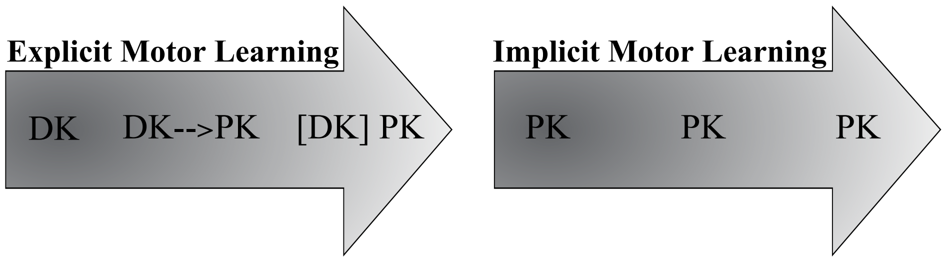


Figure 3.1. Knowledge types underlying motor control throughout explicit and implicit motor learning.[45,46] With explicit motor learning, motor control first relies on declarative knowledge (DK), which in the course of practice is gradually transformed into procedural form (PK). Although no longer essential for motor control, declarative knowledge remains accessible in the automatic phase ([DK]). In contrast, during implicit learning, motor control depends on procedural knowledge right from the outset of learning, with practice resulting in more refined procedural knowledge. Thus, although both learning modes eventually result in fully procedural motor control, only explicit learning results in the accrual of declarative knowledge. Please note that this dichotomous model is a simplified representation of motor learning. Learning is likely to involve both modes of learning in parallel or in interaction, and is not either purely implicit or purely explicit.[136–138]

Observational studies of current stroke rehabilitation practice show that physical therapists often rely on these explicit motor learning strategies: mainly providing verbal instructions and feedback concerning *how* movements should be performed, thereby eliciting conscious attempts on the part of the patients to adjust motor performance.[42,43] Theoretically, this apparent bias toward using explicit motor learning strategies should not be a cause of concern, as this mode of learning can eventually result in fully automated motor performance. However, in practice, many patients remain strongly inclined to consciously control their movements (and in a way, remain "stuck" in the verbal-cognitive phase) up to years after discharge.[28,29,134] For these patients, motor control remains highly WM-dependent and, hence, susceptible to dual-task interference.

One way to diminish this problem might be *implicit motor learning*. In contrast to explicit motor learning, implicit motor learning "… progresses with no or minimal increase in verbal knowledge of movement performance (e.g., facts and rules) and without awareness. Implicitly learned skills are (unconsciously) retrieved from implicit memory."[47(p.6)] In other words, when learning a movement implicitly, the learner largely skips the declarative phase of learning and hence acquires far less explicit movement-related knowledge. Instead, the learner directly develops procedural knowledge of the skill instead (Figure 3.1). As a result, implicit motor learning requires no or minimal conscious involvement, and only minimally loads WM. Hence, movements should be less easily disturbed by dual-task performance.

A typical example of implicit motor learning is unintentional learning, such as in the serial-reaction time (or SRT) task. For this task, participants are presented with a sequence of visual stimuli, appearing at different locations on a computer screen. Participants are required to press the button that corresponds with this location as fast as possible. Unbeknownst to the participants, stimuli are not randomly presented but follow an embedded repeating sequence. After practice, implicit motor learning is evidenced by the fact that participants generally respond significantly faster on these sequenced stimuli than on randomly presented ones, without being able to explicitly recall or recognize this learned sequence.[40,51]

Motor skills with more complex movement dynamics (e.g., balancing) can also be learned implicitly. Compared to SRT tasks, it is more difficult to learn such complex motor tasks in a purely implicit way – when learning to stabilize a balance board, learners will likely always have some explicit knowledge of how to perform the task. Nonetheless, there are implicit motor learning methods available that can minimize the involvement of such explicit processes. Although there is some debate as to the most effective method, the following three are most often used and generally agreed upon to yield reliable results:[47] 1) dual-task learning: performing an attention demanding secondary task during motor learning, which consumes large proportions of WM capacity and hence impairs the learner's ability to process movement-related knowledge.[41,49,139] A typical example is a study by Maxwell et al.[49] in which participants implicitly learned a golf-putting task by simultaneously counting tones that were presented every 1-2 seconds; 2) analogy learning: providing the learner with a metaphor that encompasses the global structure of the to-be-learned skill, such that only minimal WM involvement is required.[55,140] For example, when learning a table-tennis forehand stroke, an effective analogy is to "move the bat as though it is travelling up the side of a mountain" (Koedijker et al., *p.* 251)[140]; and 3) errorless learning: constraining the learning environment to ensure that very few errors occur and learners are not enticed to engage in (WM-demanding) hypothesis-testing behavior.[75,107] In the study by Lam et al.,[107] for instance, the occurrence of errors was minimized by having participants first put from a very short distance (0.25 cm), which was subsequently only gradually increased. Finally, although not always earmarked as such, learning using an external focus of attention (i.e., focusing attention on movement effects) may induce implicit motor skill learning, as it minimally taxes WM[57,86] and results in the accrual of limited amounts of movement-related declarative knowledge[56] – the hallmark of implicit motor learning. For instance, when taking a step, focusing externally on *where* to place your feet has been found to result in more automatic movement execution compared to focusing internally on the stepping movement itself.[86]

Within healthy adults, the paradigms outlined above have generated convincing evidence for the WM-independence of implicit motor learning. For instance, implicit motor learning seems less reliant on neural networks involved in executive WM control (i.e., prefrontal and premotor cortices[63–67]) than explicit motor learning. Also, a learner's WM capacity is not associated with the rate of implicit motor learning, while it does predict the rate of explicit learning (see Janacsek & Nemeth for a review[40]), and age-related reductions in WM capacity primarily affect explicit, not implicit, motor learning abilities.[71,72] Finally, and most importantly, numerous studies show that - compared to explicitly learned movements - the performance of implicitly acquired motor skills is more robust to concurrent performance of a wide variety of cognitive tasks. Examples include: tone-counting during golf-putting,[48,56] random-letter generation during surgical knot-tying,[108] number-recall during balancing,[111] and word-monitoring during table-tennis forehand strokes.[104,140]

Considering the promising findings within healthy adults, one would hypothesize that dual-task performance of patients with stroke can be enhanced through the use of implicit motor learning strategies during rehabilitation. However, one vital precondition must be met for this conjecture to be true, namely that patients actually retain the ability to learn implicitly after stroke. Problematically though, it is not yet clear whether and to what degree this is the case. Although several studies have reported implicit motor learning to be preserved post-stroke,[141–145] others have reported that implicit motor learning to be impaired or even absent.[146–149]

Therefore, in order to determine the suitability of implicit motor learning as an intervention during rehabilitation post-stroke, our current aim is to assess whether implicit motor learning is still possible after stroke. To this end, we will systematically review studies that have investigated implicit motor learning after stroke, focusing on the following research questions: 1) Can patients with stroke learn motor tasks implicitly – i.e., improve their motor skill, without the accrual of declarative movement-related knowledge? 2) Is implicit motor learning impaired in patients compared to healthy peers? 3) Is implicit motor learning more or less impaired than explicit motor learning following stroke?

2. Methods

2.1. Criteria for inclusion of studies

The following in- and exclusion criteria were applied in the selection of papers.

2.1.1. Population

Only studies that concerned patients with stroke were included (>18 years of age). Studies were excluded if patient groups were mixed in terms of lesion etiology (i.e., not only stroke), unless implicit motor learning could be assessed separately for the stroke group. If studies were based on the same patient cohort, only the data from the first published study was included.

2.1.2. Experimental design

Published and non-published studies that investigated implicit *motor* learning were included. Both randomized and non-randomized (i.e., quasi-randomized, controlled before-and-after studies, cohort studies, case-control studies) studies that assessed motor learning with immediate or delayed retention tests were eligible for inclusion. Case studies were excluded. Further, we only included studies that checked whether patients did not acquire explicit movement-related knowledge in the course of learning (i.e., by means of verbal reports, recognition/recall tests, or awareness tests). This because without such checks it cannot be ascertained that motor learning had indeed been implicit. As this review did not aim to assess the effect of an intervention (i.e., brain stimulation or medication) on implicit motor learning post-stroke, intervention studies were included only if they also assessed implicit motor learning within a non-exposed (i.e., placebo or control) patient group.

2.1.3. Assessment of motor learning

Studies that used (versions of) SRT paradigms were eligible for inclusion if the difference in tracking error/reaction time between random and repeated motor sequences could be obtained.[150,151] Studies that investigated learning on more complex motor tasks (i.e., balancing, grasping, walking) were included if they assessed performance improvement from baseline to post-test.

2.2. Data sources and searches

2.2.1. Database search

We searched the following databases (from inception to 1 October 2015) for relevant studies: MEDLINE, the Cochrane library, Embase, PEDro, and PsycINFO. A medical research librarian developed a sensitive search strategy, using controlled vocabulary and free text search terms. We did not impose any language restrictions. The search strategy can be divided in the following key parts: Implicit (#1), Learning (#2), Memory (#3), Motor Performance (#4), and Brain Injury (#5). These terms were adapted to each database's terminology, and if applicable, the so-called explode feature was used to search for more specific related terms. For each database, the key search features were combined in the following fashion: (#1 AND (#2 OR #3)) AND #4 AND #5. Appendix 3.1 lists the MEDLINE search strategy.

2.2.2. Grey literature and ongoing studies

Unpublished reports and conference abstracts were searched for in BIOSIS Previews, Web of Science, OpenGrey, and the British Library. To identify possibly relevant ongoing studies, national (http://www.trialregister.nl) and international trial registers (https://clinicaltrials.gov; http://apps.who.int/trialsearch/) were searched. When a possibly relevant ongoing study was found, its primary investigator was contacted to acquire further information on the study.

2.2.3. Hand searching

Reference lists of included studies and relevant reviews were screened for additional relevant studies.

2.3. Study selection

After removal of duplicates, two reviewers (EK, JvdK) independently examined titles and abstracts of all identified studies to determine their eligibility. Next, the two reviewers independently examined the full text of these studies, and applied the in- and exclusion criteria to determine their eligibility. If discrepancies existed, reviewers conferred to reach consensus on this issue. A third independent reviewer (HH) was consulted if no consensus could be reached.

2.4. Data extraction and quality assessment

The two reviewers independently extracted the following information from the included studies:

- Study population (number of participants, age, gender, time since stroke, stroke location, results of tests of cognitive and motor functioning);
- Study characteristics (type of motor task, content of training, retention on separate day (yes/no), declarative knowledge tests and their results);

- Study results: for dynamically complex motor tasks: performance improvement from pre- to post-test; For SRT-type paradigms: difference in performance on random vs. sequenced stimuli;

The two reviewers independently assessed the risk of bias of the included studies with the Newcastle-Ottawa Scale (NOS),[152] which was slightly modified for the study purpose (as recommended by the Cochrane Handbook[100]; Appendix 3.2). Three separate versions of the NOS were used. The first NOS was used to rate studies' quality to answer the main research question (Can patients with stroke learn motor tasks implicitly?). The scale contains items on participant selection, performance bias, and outcome assessment, with scores ranging from 0-8 (Appendix 3.2 – version 1). The second and third NOS were used to rate studies' risk of bias regarding the sub questions: "Is implicit motor learning impaired after stroke compared to healthy peers?" and "Is implicit motor learning more or less impaired than explicit motor learning following stroke?". These NOS scales contained the same items as the first NOS, plus items regarding group comparability. Scores could range between 0-12 (Appendix 3.2; versions 2-3). Higher NOS-scores reflect a lower risk of bias. In this review, studies could either be classified as exhibiting a high (NOS-1: 0-4; NOS-2&3: 0-8), moderate (NOS-1: 5-6; NOS-2&3: 9-10), or low risk of bias (NOS-1: 7-8; NOS-2&3: 11-12).

2.5. Data synthesis and analysis

Data pooling was carried out with RevMan 5.3 (The Nordic Cochrane Centre, Copenhagen, Denmark) by two authors (EK/MW). We planned analyses for all three research questions. Based on clinical grounds, we a priori decided to only pool data when similar task paradigms and motor effectors were used (e.g., lower/upper limb; affected/unaffected side/bilateral involvement). From a clinical point of view, this distinction is relevant, as rehabilitation practice is primarily concerned with restoring motor function of the patient's affected side, rather than the unaffected side. In addition, from a theoretical point of view, this approach also allowed us to assess whether stroke patients suffer from general, effector-independent implicit learning deficits (i.e., a general deficit in sequencing each sub-movement of the motor skill, regardless of the extremity involved), and/or from effector-dependent impairments (i.e., a specific deficit in learning the performance of each sub-movement using the most-affected extremity; see[153–155]).

When studies used the same outcome measure (with similar units of measurement) data were pooled using the mean difference (MD). For studies that used different outcome measures we used the standardized MD (SMD; i.e., Cohen's *d* corrected for bias in studies with small samples[156]). Significance level was set at $p<0.05$. A fixed effects model was used to pool data when studies were statistically homogenous, or when fewer than 5 studies were available for data synthesis. A random effects model was only used when both heterogeneity was present and when more than 5 studies were available. Statistical heterogeneity was assessed by visually inspecting the forest plots, and by means of the I^2-statistic, with heterogeneity being present when the X^2 was significant ($p < 0.1$).[100] Causes of statistical heterogeneity were further explored with meta-regression or subgroup analyses, if appropriate (i.e., ≥ 10 studies available for synthesis). With regard to the latter, we specifically planned subgroup analyses to explore whether statistical heterogeneity was due to between-study differences between studies in patients' lesion location. For this purpose, we classified the lesion location of patients in each study (i.e., cortical, subcortical, mixed cortical/subcortical, cerebellar stroke).[157] Descriptive synthesis was presented in case data pooling was not considered feasible. A funnel plot was used to investigate the presence of publication bias.[119]

3. Results

3.1. Literature search

In total, our search identified 2177 reports. After removal of duplicates and screening of titles and abstracts, full text reports were obtained for 70 studies. Application of the in- and exclusion criteria eventually resulted in the inclusion of 20 studies (see Figure 3.2). Most of the excluded studies included heterogenic patient groups (i.e., not (only) stroke; n = 20), or did not check whether learning had been implicit (n = 19). Despite successive attempts, no full text could be obtained for 2 studies.[158,159] Note that two of the included studies were written in Korean.[160,161] These were translated into English by a native Korean scientist with experience in the field of (implicit) motor learning. Inspection of a funnel plot of all included studies revealed no evidence of publication bias, considering its symmetrical distribution (See Appendix 3.3).[119]

3.2. Study characteristics

Appendix 3.4 summarizes the characteristics of the 20 included studies.

3.2.1. Design and implicit motor learning paradigms

With the exception of two studies,[148,162] all studies compared implicit motor learning abilities of patients with stroke with those of healthy age-matched controls. Four studies also contrasted the effectiveness of implicit motor learning and explicit motor learning after stroke.[75,141,144,148] Note that several studies incorporated multiple stroke patient groups.[75,143,148,163,164] With regards to the experimental paradigm used, almost all studies have focused on motor learning involving the upper extremity. Specifically, most studies (N = 14) investigated implicit motor learning using the SRT-paradigm.[141,143,145,147–149,160–162,165–169] Adapted versions of this SRT-paradigm were also used, either in the form of the so-called serial hand movement (SHM) paradigm (N = 2)[164,170] or continuous tracking (CTT) task (N = 2).[144,171] Both these paradigms are essentially similar to the SRT, but require slightly more complex hand movements such as the handling of switches (SHM) or tracking of a continuously moving target with a hand-held stylus (CTT). In one study patients learned both the SRT and SHM task,[163] to explore if task difficulty influences motor learning ability post stroke. Importantly, almost all of the above studies investigated implicit motor learning using the relatively unaffected upper extremity (N = 13).[141,143–145,147,148,160,161,163–165,169,170] Four studies also investigated implicit motor learning using the affected upper extremity,[145,147,162,171] whereas in four other studies motor performance required bilateral movements (i.e., the middle and index finger of each hand).[149,166–168] Finally, only one study assessed implicit motor learning within the context of learning a dynamically more complex motor task – stabilizing a balance board using an errorless learning approach.[75]

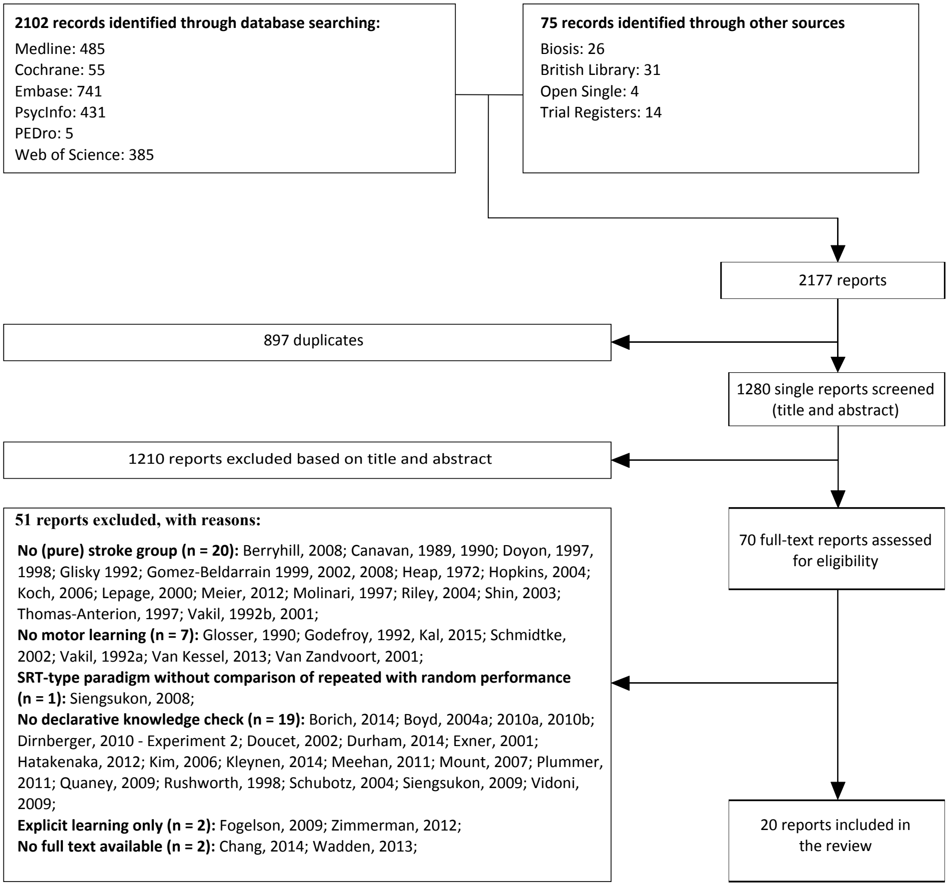


Figure 3.2. Flowchart of inclusion of studies. Note that only experiment 1 of the study of Dirnberger et al.[166] was included, while experiment 2 was excluded. Therefore, although 51 out of the available 70 reports were excluded after full-text screening, 20 reports were included.

3.2.2. Participants

In total, 337 patients and 253 controls participated in the selected studies. Across studies, considerable heterogeneity was noted in terms of patient characteristics, such as patients' mean age (range: 46-74 years), time since stroke (range: 1.9-88 months) and lesion location. With regard to the latter, three studies investigated patients with isolated cerebellar lesions,[147,166,167] six studies incorporated patient groups with isolated supratentatorial subcortical lesions,[144,145,149,165,168,171] four studies studied patient groups with mixed supratentatorial subcortical- and/or cortical lesions,[143,148,162,163] while 2 studies incorporated patient groups with mixed sub- and supratentatorial lesions.[75,148] Finally, in five studies lesion location was only described as being supratentatorial and not further specified.[160,161,164,169,170]

Table 3.1. NOS-scores of included studies.

Study	**NOS-1: Implicit motor learning in stroke (0-8)**	**NOS-2: Implicit motor learning in stroke vs. controls (0-12)**	**NOS-3: Implicit vs. explicit motor learning in stroke (0-12)**
Boyd & Winstein, 2001[148]	5.5		6
Boyd & Winstein, 2003[141]	7	9	11
Boyd & Winstein, 2004[144]	7	9	10
Boyd et al., 2007[163]	4	6	
Boyd et al., 2009[165]	5	7	
Dirnberger et al., 2010 – Experiment 1[166]	6	9	
Dirnberger et al., 2013[167]	6	8	
Dovern et al., 2011[143]	3	3	
Exner et al., 2002[168]	5	6	
Gomez et al., 1998[147]	2	3	
Lee et al., 2006[160]	2	2	
Lee et al., 2008[161]	1	1	
Meehan et al., 2011[171]	6	8	
Orrell et al., 2006[75]	6	9	10
Orrell et al., 2007[169]	4	5	
Pohl et al., 2001[170]	3	6	
Pohl et al., 2006[164]	3	6	
Rösser et al., 2008[162]	3		
Shin et al., 2005[145]	1	2	
Vakil et al., 2000[149]	3	5	

NB: Scores are presented separately for each research question. Colours indicate overall risk of bias assessment, with darker grey indicating high risk of bias, grey indicating moderate risk of bias, and lighter grey representing low risk of bias.

3.3. Quality assessment

Table 3.1 shows the NOS-scores of each study. Overall, most studies exhibited moderate to high risk of bias (see the supplementary material for justification of NOS-scores). This was for a large part due to lack of detail on participant screening and selection,[cf.162] lack of assessment of/correction for confounding factors,[141,143–145,149,160,161,163–165,167–171] and lack of reporting on the amount of participants' explicit movement-related knowledge.[143,145,147,160–162,164,170] In fact, in some studies participants gained so much explicit knowledge that learning may have been explicit, rather than implicit.[149,163,165,169]

3.4. Data synthesis

3.4.1. Research question 1: Can patients with stroke learn motor tasks implicitly?

<u>3.4.1.1. SRT-Type tasks - Learning using the unaffected upper-extremity</u>

Of the thirteen studies that investigated implicit motor learning using the unaffected upper extremity, eleven were eligible for data pooling.[141,143,145,147,148,160,161,163–165,170] For one study no information on the variance of the learning effect could be obtained.[169] Therefore, this study is discussed in the descriptive synthesis section below, along with one study by Boyd and Winstein[144] which could also not be included in the meta-analysis. This because in this latter study a CTT paradigm was used to assess implicit motor learning, measuring the learning effect in percentage RMSE. This is in contrast to the other eleven SRT- and SHM-studies, which measured learning in milliseconds. Technically we could have pooled all twelve studies with SMDs. However, this would have violated the assumption that between-study variation in SDs is due to the use of different measurement scales rather than to differences in variability among study populations.[100] Therefore, we chose not to do this and only descriptively present Boyd and Winstein's[144] findings.

Meta-analysis: The eleven studies that were pooled incorporated 15 stroke groups. A random effects model was used with the mean difference in reaction time between random and repeated blocks serving as outcome measure. Results showed that patients demonstrated significant implicit motor learning with their unaffected hand, as evidenced by faster reaction times on the repeated compared to the random blocks (MD = 69 ms, 95% CI = [45.1, 92.9], Z = 5.66, $p < .00001$; Figure 3.3). Considerable statistical heterogeneity was present ($I^2 = 87\%$). We performed a subgroup analysis to see whether this heterogeneity was due to differences in patients' lesion location. Results confirmed that learning ability differed as a function of lesion location ($Chi^2 = 20.66$, $p = .0001$; $I^2 = 86\%$). Specifically, only patients with isolated subcortical lesions did not show significant learning (MD = 37.7 ms, [-69.0, 144.4], Z = 0.69, $p = .49$). Too few studies were available to further explore possible other causes of the statistical heterogeneity.

Descriptive synthesis: The results of Orrell et al.[169] seem largely in line with findings of the above meta-analysis. Specifically, they found that patients with supratentatorial brain damage demonstrated learning; at the end of two days of practice, patients' reaction times were 96 ms faster for the repeated than for the random blocks. Although the exact significance of this learning effect is unclear, its magnitude seems in line with the findings of our meta-analysis of studies with mixed cortical/subcortical patient populations (Figure 3.3).

The results of Boyd and Winstein[144] seemed to deviate from those of the meta-analysis, though. In this study, patients with lesions in the supratentatorial subcortex practiced a CTT task on three consecutive days. Different from their peers in the meta-analysis, patients demonstrated significant learning, as evidenced by less tracking error on repeated versus random stimuli (ΔRMSE = 6.4%, SE = 0.98, $t(1,4) = 6.5$; $p < .01$). We therefore performed a sensitivity analysis to check whether exclusion of Boyd and Winstein[144] influenced our meta-analysis. We transformed their learning score into milliseconds (based on the SMDs[100]) and added them to the meta-analysis. The pooled estimate did not change (MD = 70 ms, 95% CI = [46.2, 93.5], Z = 5.78, $p < .00001$; $I^2 = 86\%$), neither did the subgroup-analysis ($Chi^2 = 20.53$, $p = .0001$; $I^2 = 85\%$). Thus, learning remained non-significant for the subcortical group, even when Boyd and Winstein's findings were added to the analysis (MD = 52.77 ms, [-40.0, 145.5], Z = 1.12, $p = .26$).

3.4.1.2. SRT-Type tasks - Learning using the affected upper extremity

Meta-analysis: Four studies investigated implicit motor learning using the affected upper extremity, one of which used the CTT paradigm[171] and three the SRT-paradigm.[145,147,162] Two studies involved patients with isolated supratentatorial subcortical lesions,[145,171] one study concerned a mixed patient population (mixed supratentatorial cortical/subcortical lesions),[162] and one study included isolated cerebellar lesions.[147] Data was pooled using a fixed effects model with the standardized mean difference in performance between repeated and random blocks as outcome measure. The pooled estimate showed no significant implicit motor learning (SMD = -.11, 95% CI [-.45, .25], Z = .59, $p = .56$; Figure 3.4). Not enough studies were available (N > 10) to analyze the moderate statistical heterogeneity ($I^2 = 57\%$, $p = 0.07$).

3.4.1.3. SRT-Type tasks - Learning using both hands

Four studies investigated implicit motor learning with SRT-paradigms that required bimanual responses.[149,166–168] The study of Vakil et al.[149] could not be pooled with the other three studies, as the variance of the learning effect could not be obtained. Its results are therefore presented in the descriptive synthesis section.

Meta-analysis: Studies either included patients with isolated cerebellar lesions[166,167] or with isolated supratentatorial subcortical lesions.[168] We pooled results using a fixed effects model with the mean difference in reaction time between repeated and random blocks as outcome measure (Figure 3.5). Overall, learning was significant (MD = 40.7 ms, 95% CI [32.0, 49.4], Z = 9.2, p < .00001). Statistical heterogeneity was negligible (I^2 = 10%).

Descriptive synthesis: In Vakil et al.[149] patients with isolated supratentatorial subcortical lesions practiced the SRT-task within one day. At the end of practice, patients responded faster (36 ms) on repeated than on random blocks. Although it is unclear whether this finding was statistically significant, the magnitude of the effect seems similar to the meta-analysis of the other three studies.

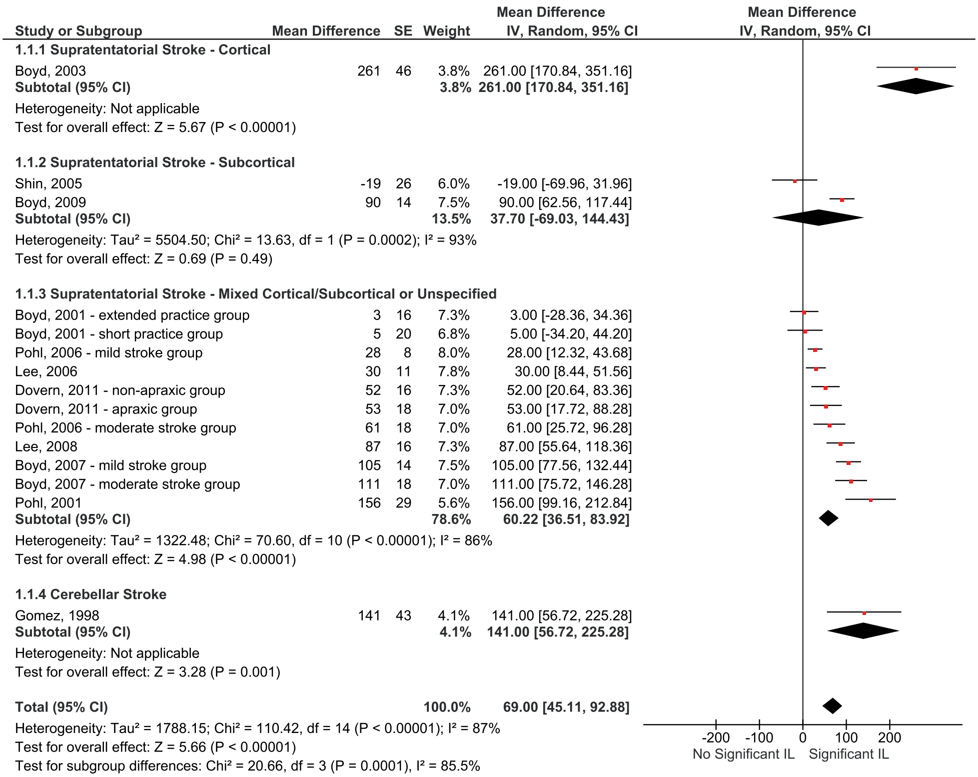


Figure 3.3. Pooled results of SRT-/SHM-studies that investigated implicit motor learning after stroke for the unaffected hand. Results concern the mean differences in reaction time (in ms) between repeated and random blocks. Square size indicates a study's relative contribution to the pooled estimate. Diamond width indicates the 95% confidence interval of the pooled effect. Note that Boyd et al.[163] tested patients on both a SHM and a SRT paradigm. We therefore collapsed the data for each group across these paradigms, following Cochrane recommendations.[100] NB: CI = confidence interval; IL = implicit motor learning; IV = inverse variance; SE = standard error;

Study or Subgroup	Std. Mean Difference	SE	Weight	Std. Mean Difference IV, Fixed, 95% CI
Gomez, 1998	-0.333	0.3	36.5%	-0.33 [-0.92, 0.25]
Rosser, 2008	-0.266	0.256	50.2%	-0.27 [-0.77, 0.24]
Shin, 2005	0.896	1.281	2.0%	0.90 [-1.61, 3.41]
Meehan, 2011	1.151	0.539	11.3%	1.15 [0.09, 2.21]
Total (95% CI)			**100.0%**	**-0.11 [-0.46, 0.25]**

Heterogeneity: Chi² = 7.01, df = 3 (P = 0.07); I² = 57%
Test for overall effect: Z = 0.59 (P = 0.56)

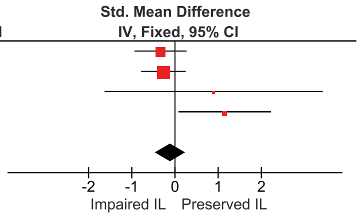


Figure 3.4. Pooled results of SRT-/CTT-studies that investigated implicit motor learning after stroke for the affected hand. Results concern the standardized mean differences in reaction time (in ms, for SRT-/SHM-studies) or RMSE (in percentages, for CTT-studies) between repeated and random blocks. Square size indicates a study's relative contribution to the pooled estimate. Diamond width indicates the 95% confidence interval of the pooled effect. NB: CI = confidence interval; IL = implicit motor learning; IV = inverse variance; SE = standard error;

Study or Subgroup	Mean Difference	SE	Weight	Mean Difference IV, Fixed, 95% CI
Dirnberger, 2010 Exp1	14	41	1.2%	14.00 [-66.36, 94.36]
Exner, 2002	29	10	19.8%	29.00 [9.40, 48.60]
Dirnberger, 2013	44	5	79.1%	44.00 [34.20, 53.80]
Total (95% CI)			**100.0%**	**40.68 [31.97, 49.40]**

Heterogeneity: Chi² = 2.23, df = 2 (P = 0.33); I² = 10%
Test for overall effect: Z = 9.15 (P < 0.00001)

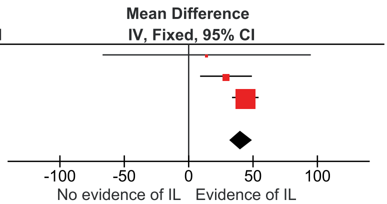


Figure 3.5. Pooled results of SRT-studies that investigated implicit motor learning after stroke with both hands. Results concern the mean differences in reaction time (in ms) between repeated and random blocks. Square size indicates a study's relative contribution to the pooled estimate. Diamond width indicates the 95% confidence interval of the pooled effect. NB: CI = confidence interval; Exp1 = experiment 1; IL = implicit motor learning; IV = inverse variance; SE = standard error;

3.4.1.4. Motor tasks with more 'complex' movement dynamics

As noted earlier, only one study investigated implicit motor learning abilities after stroke on a whole body task (Orrell et al.[75]). In this study five patients (a mix of patients with supra- and subtentatorial lesions) practiced a balance board task. Implicit motor learning was induced by means of an errorless learning approach, by progressively increasing task difficulty through reduction of the balance board's rotational resistance across practice. Balance performance significantly improved after practice, an improvement that was maintained up to one week later at a delayed retention test ($F(2,17) = 2.64$, $p = .10$).

3.4.2. Research Question 2: Is patients' implicit motor learning ability impaired compared to that of healthy peers?

3.4.2.1. SRT-Type tasks - Learning using the unaffected upper-extremity

Twelve studies contrasted implicit motor learning involving the unaffected hand in patients with healthy controls. Ten of these were eligible for data pooling. One study by Boyd and

Winstein[144] apparently concerned the same control group as an earlier study of Boyd and Winstein.[141] As we could not include the same control group twice in our analysis, a computer randomly determined which results to include in the meta-analysis (i.e., in this case Boyd & Winstein, 2003)[141].

Meta-analysis: The 10 studies' results were pooled with a random effects model with the mean difference in reaction time between random and repeated blocks as outcome measure (Figure 3.6). Overall, patients demonstrated unimpaired implicit motor learning with their unaffected hand (MD = -7.5 ms, 95% CI = [-34.3, 19.2], Z = .55, p = .58). Considerable statistical heterogeneity was present (I^2 = 66%). As for the first research question, subgroup analyses revealed that this may in part be due to the fact that learning ability differed as a function of lesion location (Chi^2 = 18.9, p = .0003): Implicit motor learning was significantly impaired in patients with isolated supratentatorial subcortical lesions (MD = -81.4 ms, [-123.5, -39.4], Z = 3.8, p = .0001), but not in the other patient groups. Additional causes for the statistical heterogeneity could not be explored.

Descriptive synthesis: The results of Orrell et al.[169] differ slightly from those of the meta-analysis, as they found that patients with supratentatorial brain damage showed less pronounced learning than healthy controls (i.e., 96 ms for stroke vs.177 ms for controls at the end of day 2; $F(2,12) = 6.93$; $p < .01$).

3.4.2.2. SRT-Type tasks - Learning using the affected upper-extremity

Meta-analysis: Three studies contrasted cerebellar[147] and supratentatorial subcortical[145,171] patients' implicit motor learning abilities using the affected upper extremity with healthy controls. One study used the CTT paradigm[171] and 2 studies used the SRT-paradigm.[145,147] Pooling entailed a fixed effects model with standardized mean difference in performance between repeated and random blocks as outcome measure (Figure 3.7). Implicit motor learning of patients was not significantly different from controls (SMD = -.51, 95% CI [-1.1, .10], Z = 1.63, p = .10). Too few studies (N < 10) were available to investigate the considerable statistical heterogeneity (I^2 = 85%).

3.4.2.3. SRT-Type tasks - Learning using both hands

Four studies compared patients' implicit motor learning abilities with those of healthy controls, all of them using SRT-paradigms that require bimanual responses.[149,166–168] Similar to the first research question, the study of Vakil et al.[149] is discussed in the descriptive synthesis section.

Meta-analysis: Studies either involved cerebellar[166,167] or supratentatorial subcortical[168] patients. We pooled results using a fixed effects model with the mean difference in reaction time between repeated and random blocks as outcome measure (Figure 3.8). Overall, implicit motor learning was found to be significantly impaired (MD = -29.9 ms, 95% CI [-51.7, -8.0], Z = 2.68, p = .007). No statistical heterogeneity was noted (I^2 = 0%).

Descriptive synthesis: The results of Vakil et al.[149] confirm the results of the meta-analysis. Patients with lesions in the supratentatorial subcortex showed impaired learning (36 ms) compared to healthy controls (97 ms) as evidenced by a significant Group by Block interaction (F(1,30) = 5.96; p < .05).

3.4.2.4. Motor tasks with more 'complex' movement dynamics

Results of Orrell et al.[75] showed that patients who engaged in errorless learning during balance training showed similar improvement in and retention of balancing performance as did healthy controls (i.e., no significant interaction; F(2,17) = 0.39; p = .70).

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
2.1.1 Supratentatorial Stroke - Cortical								
Boyd, 2003	261	102	5	144	83	5	4.1%	117.00 [1.73, 232.27]
Subtotal (95% CI)			**5**			**5**	**4.1%**	**117.00 [1.73, 232.27]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.99 (P = 0.05)								
2.1.2 Supratentatorial Stroke - Subcortical								
Boyd, 2009	90	51	13	179	102	13	8.9%	-89.00 [-150.99, -27.01]
Shin, 2005	-19	52	4	56	35	7	9.6%	-75.00 [-132.18, -17.82]
Subtotal (95% CI)			**17**			**20**	**18.6%**	**-81.44 [-123.46, -39.41]**
Heterogeneity: Tau² = 0.00; Chi² = 0.11, df = 1 (P = 0.74); I² = 0%								
Test for overall effect: Z = 3.80 (P = 0.0001)								
2.1.3 Supratentatorial Stroke - Mixed Subcortical/Cortical or Unspecified								
Boyd, 2007 - combined	107	57	28	144	75	17	12.2%	-37.00 [-78.43, 4.43]
Pohl, 2006 - combined	41	54	37	54	86	30	13.2%	-13.00 [-48.35, 22.35]
Lee, 2006	30	50	20	35	53	20	13.8%	-5.00 [-36.93, 26.93]
Pohl, 2001	156	199	47	145	210	36	5.9%	11.00 [-78.12, 100.12]
Dovern, 2011 - combined	53	84	48	40	48	17	13.7%	13.00 [-19.94, 45.94]
Lee, 2008	87	56	12	56	34	12	12.9%	31.00 [-6.07, 68.07]
Subtotal (95% CI)			**192**			**132**	**71.8%**	**-0.49 [-19.40, 18.41]**
Heterogeneity: Tau² = 157.77; Chi² = 7.02, df = 5 (P = 0.22); I² = 29%								
Test for overall effect: Z = 0.05 (P = 0.96)								
2.1.4 Cerebellar Stroke								
Gomez, 1998	141	160	14	80	68	10	5.5%	61.00 [-32.81, 154.81]
Subtotal (95% CI)			**14**			**10**	**5.5%**	**61.00 [-32.81, 154.81]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.27 (P = 0.20)								
Total (95% CI)			**228**			**167**	**100.0%**	**-7.51 [-34.27, 19.25]**
Heterogeneity: Tau² = 1082.53; Chi² = 26.36, df = 9 (P = 0.002); I² = 66%								
Test for overall effect: Z = 0.55 (P = 0.58)								
Test for subgroup differences: Chi² = 18.92, df = 3 (P = 0.0003), I² = 84.1%								

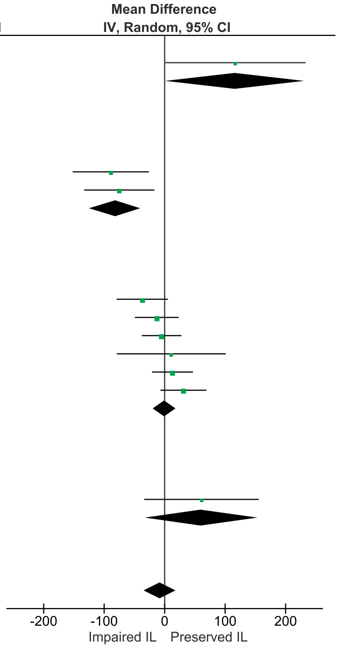


Figure 3.6. Pooled results of SRT-/SHM-studies that compared implicit motor learning for the unaffected hand between patients with stroke and healthy controls. Results concern the mean differences in reaction time (in ms) between repeated and random blocks for both groups. Square size indicates the study's sample size. Diamond width indicates the 95% confidence interval of the pooled effect. Note that we collapsed the data for studies that included multiple stroke patient groups, as these studies only incorporated one healthy control group (following Cochrane recommendations[100]). NB: CI = confidence interval; IL = implicit motor learning; IV = inverse variance; SD = standard deviation;

Study or Subgroup	Std. Mean Difference	SE	Stroke Total	Control Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Gomez, 1998	-1.796	0.488	14	10	40.4%	-1.80 [-2.75, -0.84]
Shin, 2005	-0.34	0.712	4	7	19.0%	-0.34 [-1.74, 1.06]
Meehan, 2011	0.697	0.486	9	9	40.7%	0.70 [-0.26, 1.65]
Total (95% CI)			**27**	**26**	**100.0%**	**-0.51 [-1.11, 0.10]**

Heterogeneity: Chi² = 13.17, df = 2 (P = 0.001); I² = 85%
Test for overall effect: Z = 1.63 (P = 0.10)

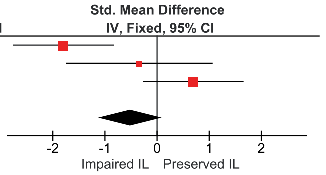


Figure 3.7. Pooled results of SRT-/CTT-studies that compared implicit motor learning for the affected hand between patients with stroke and healthy controls. Results concern the standardized mean differences in reaction time (in ms, for SRT-studies) or RMSE (in percentages, for CTT-studies) between repeated and random blocks. Square size indicates a study's relative contribution to the pooled estimate. Diamond width indicates the 95% confidence interval of the pooled effect. NB: CI = confidence interval; IL = implicit motor learning; IV = inverse variance; SE = standard error;

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Fixed, 95% CI
Dirnberger, 2010 Exp1	14	131	10	59	103	12	4.8%	-45.00 [-144.94, 54.94]
Dirnberger, 2013	44	15	10	85	56	12	43.8%	-41.00 [-74.02, -7.98]
Exner, 2002	29	45	20	48	53	20	51.4%	-19.00 [-49.47, 11.47]
Total (95% CI)			**40**			**44**	**100.0%**	**-29.88 [-51.73, -8.03]**

Heterogeneity: Chi² = 1.01, df = 2 (P = 0.60); I² = 0%
Test for overall effect: Z = 2.68 (P = 0.007)

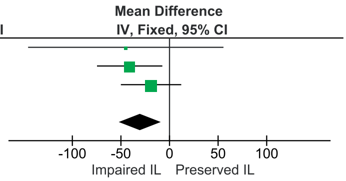


Figure 3.8. Pooled results of SRT-studies that compared implicit motor learning with both hands by patients with stroke and healthy controls. Results concern the mean differences in reaction time (in ms) between repeated and random blocks. Square size indicates a study's sample size. Diamond width indicates the 95% confidence interval of the pooled effect. NB: CI = confidence interval; Exp1 = experiment 1; IL = implicit motor learning; IV = inverse variance; SD = standard deviation;

3.4.3. Research Question 3: Is implicit motor learning more or less impaired than explicit motor learning following stroke?

3.4.3.1. SRT-Type Tasks - Learning using the unaffected upper-extremity

All identified SRT-type studies that contrasted implicit and explicit motor learning post-stroke concerned learning with the unaffected hand. No studies were found that focused on learning using the more affected extremity.

Meta-analysis: Three studies contrasted implicit and explicit motor learning abilities of patients with isolated subcortical,[144] cortical,[141] and mixed subcortical/cortical supratentatorial lesions.[148] Two studies used a SRT-paradigm[141,148] while one study used a CTT paradigm.[144] Data pooling entailed a fixed effects model with the standardized mean difference in performance between random and repeated blocks as outcome measure. Overall, implicit learning did not result in superior learning compared to explicit learning (SMD = -.54, 95% CI[-1.37, .29], Z = 1.27, p = 0.20; Figure 3.9). Considerable heterogeneity was present (61%), but could not be further investigated.

3.4.3.2. Motor tasks with more 'complex' movement dynamics

In line with the above meta-analysis, the study by Orrell et al.[75] reported that patients who had implicitly learned the balancing task (with errorless learning) demonstrated a similar improvement in balance skill as those patients who had explicitly learned this task (through discovery learning). Specifically, at the delayed retention test one week post-practice, the implicit group's performance did not significantly differ from that of the explicit group ($M_{Implicit}$ = 8.8±1.5 RMSE; $M_{Explicit}$ = 9.0±0.6 RMSE; $t(1,8) = 0.28$; $p = .79$).

Study or Subgroup	Explicit Mean	Explicit SD	Explicit Total	Implicit Mean	Implicit SD	Implicit Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Boyd, 2001 - short practice group	47	37	4	5	41	4	29.6%	0.94 [-0.59, 2.46]
Boyd, 2003	138	94	5	261	102	5	35.5%	-1.13 [-2.53, 0.26]
Boyd, 2004	4.2	0.9	5	6.4	2.2	5	34.9%	-1.18 [-2.59, 0.22]
Total (95% CI)			**14**			**14**	**100.0%**	**-0.54 [-1.37, 0.29]**

Heterogeneity: Chi² = 5.08, df = 2 (P = 0.08); I² = 61%
Test for overall effect: Z = 1.27 (P = 0.20)

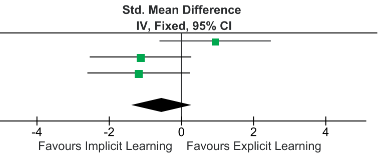


Figure 3.9. Pooled results for SRT-/CTT-studies that compared the effectiveness of implicit and explicit motor learning for the unaffected hand post-stroke. Results concern the standardized mean differences in reaction time (in ms, for SRT-studies) or RMSE (in percentages, for CTT-studies) between repeated and random blocks. Square size indicates a study's relative contribution to the pooled estimate. Diamond width indicates the 95% confidence interval of the pooled effect. NB: CI = confidence interval; IV = inverse variance; SD = standard deviation;

4. Discussion

4.1. Principal findings

The aim of this review was to determine the extent to which implicit motor learning is possible after stroke. Specifically, we investigated whether patients with stroke could significantly improve their motor performance through implicit motor learning, as well as how patients' implicit motor learning abilities compare to healthy peers. Furthermore, we scrutinized evidence to determine whether implicit motor learning is more or less effective than explicit motor learning post-stroke.

In total, we identified 20 studies that investigated implicit motor learning after stroke. Of note, limited information was available on implicit motor learning in clinically relevant settings. Specifically, only one study[75] investigated implicit motor learning in a clinically relevant balancing task, but all other studies concerned adaptations of the classic SRT-paradigm. Relatedly, the majority of studies investigated learning with the relatively unaffected side, and only few studies were concerned with patients' ability to learn with their affected or paretic side (i.e., four studies[145,147,162,171] concerned the affected extremity, while five studies[75,149,166–168] required bilateral involvement).

The meta- and descriptive syntheses suggested that patients generally show significant and unimpaired implicit motor learning with their unaffected hand. An exception may be patients with subcortical lesions, as they overall did not demonstrate significant learning and were significantly impaired compared to healthy peers. Learning tended to be less consistent and more impaired when the paretic hand was involved. Based on the four studies that contrasted implicit motor learning with explicit motor learning, it may be that both modes of learning are equally preserved after stroke.

However, as of yet any conclusions regarding the above findings must be considered premature, due to three main reasons. First and foremost, reliable interpretation of these findings is compromised due to the overall high risk of bias that was noted across studies. This bias was mostly due to insufficient reporting on participant selection, explicit knowledge, and group comparability. Second, studies were generally of limited clinical relevance, since almost all concerned SRT-type tasks and/or only focused on patients' ability to learn with their relatively unaffected side. Finally, most studies consisted of quite small sample sizes (i.e., M = 14 patients per group). As a result, it is yet premature to draw any conclusions regarding implicit motor learning abilities of people with stroke, let alone regarding its effectiveness and suitability for clinical practice. Nevertheless, the current findings seem appropriate as a starting point for building hypotheses for future research. Below, we will discuss these hypotheses as well as other implications of our findings for research and clinical practice. First, though, we will shortly discuss the reasons for the risk of bias among the included studies.

4.2. Risk of bias assessment

With the exception of two studies,[141,144] all studies were subject to a moderate to high risk of bias. This was due to a variety of reasons. First, all but one study[162] failed to clearly describe the screening and selection of subjects, while most studies also lacked proper description of participants' characteristics (e.g., in terms of motor and/or cognitive functioning).[145,148,149,160,161,164] Further, a significant limitation of those studies that contrasted implicit motor learning of patients with healthy controls is the lack of information regarding group comparability. Confounders such as motor or cognitive functioning often were neither reported for the patient and control groups,[141,143,144,149,160,161,163,165,167–171] nor matched across groups or corrected for in the analysis of implicit motor learning.[141,143–145,160,161,163–165,169,171] This makes it difficult to assess the representativeness of patients of the general stroke population and the comparability of stroke and control groups, resulting in a high risk of selection bias. We acknowledge that it may be challenging to find appropriate measurement scales to reliably compare stroke patients' motor abilities with those of healthy elderly, as the latter will generally achieve maximum scores on stroke-specific instruments, such as the Fügl-Meyer Assessment or Motricity Index. To circumvent this problem, some studies in our review used initial performance during the first block of practice as a measure of baseline motor ability. However, this is not a valid method, as these values will be influenced by the experimental manipulation. Therefore, we strongly recommend to incorporate task-relevant alternatives that do not have a ceiling effect, such as the fast-tapping task used in the SRT-study by Shin et al.[145] Alternatively, authors may also conduct pre-test measurements of the to-be learned motor task**.** When groups differ in motor ability, a statistical correction for motor ability is warranted, for instance by means of analysis of covariance.

On a different note, the risk of so-called performance bias was high as well. For several studies we could not determine the likelihood that patients indeed learned implicitly rather than explicitly, either because only very superficial explicit knowledge checks were used – merely probing patients whether they noticed anything about the task[147,160–162] – or because it was unclear if patients' explicit knowledge exceeded chance levels.[143,145,164,170] In other studies patients had acquired so much explicit task-related knowledge that it is not unlikely that they at least partially engaged in explicit motor learning.[149,163,165,169]

A final limitation of a considerable number of studies was that practice sessions were of very short duration – i.e., learning was assessed within a single practice session within one day, without delayed retention tests.[143,145,147,161–164,166–168] This can be problematic for two reasons. First, such a short practice period might have limited these studies' power to find significant learning effects, as implicit learning is considered to be a relatively slow process.[49,172] Second, learning effects that are observed immediately after practice can substantially differ from those assessed following a delay period (i.e., > 24 hours following the end of practice)[61,98] This latter issue may also have contributed to the statistical heterogeneity noted in our meta-analyses.

Overall, the points outlined above added up to a considerable risk of bias in most studies.

4.3. Implications for research

The findings of this review largely leave unanswered our previous question, but allow further specification of these questions for future studies to answer: (1) Do patients with stroke remain able to learn clinically relevant, complex motor tasks with their affected side in an implicit way?; (2) Are implicit and explicit motor learning equally preserved post-stroke?; and (3) How do different lesion locations (and especially subcortical lesions) affect the effectiveness of implicit and explicit motor learning post-stroke?

Considering the risk of bias issues outlined in the previous section, we recommend that studies that investigate these and other hypotheses regarding implicit motor learning post-stroke comprehensively report their procedures and findings, using checklists like the STROBE and CONSORT statements.[121,122] Studies should especially include proper manipulation checks, by documenting the amount of participants' explicit movement-related knowledge after practice. Another seemingly obvious, yet currently often not met requirement for further studies is to incorporate appropriate sample sizes, preferably based on power analysis

On a different note, future studies should consider the clinical relevance of the to-be learned motor task. As highlighted by the current review, studies into implicit motor learning after stroke have mostly been restricted to SRT-type paradigms, in which patients practiced with their relatively unaffected hand over a relatively short period of time. The results obtained with these types of paradigms may not be easily generalizable to more complex motor tasks of daily living (i.e., walking, grasping, and balancing).[95] Therefore, for implicit motor learning to have any clinical utility it must be determined whether patients post-stroke are able to learn these more complex motor tasks in an implicit way. To this end, future studies should test the effectiveness and feasibility of the implicit learning paradigms briefly outlined in the introduction: dual-task learning,[41] errorless learning,[107] analogy learning,[140] and external focus learning.[86] These paradigms have been shown to successfully effectuate implicit motor learning across a wide range of tasks in non-neurologically impaired individuals,[49,55–57,75,86,107,139,140] but remain virtually untested in people with stroke. Further, for greater clinical relevance, outcome measures outside the context of the trained motor task should be incorporated (e.g., dual-task performance, fall-risk, patient reported outcome measures, quality of life questionnaires). Also, these implicit learning methods need to be contrasted with explicit motor learning - which seems the “default” mode of learning during physical therapy post-stroke.[42,43] Finally, researchers may also want to consider the stratification of patients according to their lesion location, to assess if and how lesion location influences the effectiveness of implicit (and explicit) motor learning interventions (especially focussing on the influence of subcortical damage).

The above recommendations can be best implemented in randomized controlled trials (RCTs) that compare the effectiveness of implicit and explicit motor learning interventions post-stroke.

4.4. Implications for practice

As of yet, it remains unclear to what extent implicit motor learning is possible in people with stroke. Also there is a significant lack of studies that investigated implicit motor learning on tasks of greater complexity in movement dynamics and with more clinical relevance than the SRT-paradigm. Therefore, from a scientific point of view, the implementation of implicit motor learning techniques in rehabilitation therapy post-stroke is premature. This is not to say that therapists should refrain from exploring interventions that promote implicit – or explicit – motor learning when treating their patients. Several of the abovementioned techniques (dual-task learning, errorless learning, analogy learning, learning with external focus instructions) may well prove useful, if only to expand a therapist’s toolbox in treating his/her patients. In this light the case-series by Kleynen et al.[173] may be of interest, as it illustrates how analogy learning can be used to improve gait in people with stroke. In any event, it is important that therapists are aware that the effectiveness of any of these interventions to promote implicit motor learning in people with stroke has not yet been proven.

4.5. Strengths and limitations

This study is the first to systematically review implicit motor learning in people with stroke. The sensitive search strategy allowed us to search as broad as possible, identifying papers from grey literature as well as from conventional databases. Also, rating the studies' risk of bias aided the interpretation of the reliability and generalizability of the findings of this review. Nonetheless, several limitations should be noted. First, it cannot be ruled out that our review was subject to publication bias, in that we might have failed to identify non-significant and non-published studies. Also, as noted in section 3.1., no full text could be obtained for two possibly relevant studies. It seems unlikely that this resulted in publication bias, though, since our funnel plot (Appendix 3.3) did not provide any indication of this. A second limitation of the current review concerns our inclusion criterion that studies needed to include a manipulation check as to the degree to which motor learning was more implicit or explicit. As a result, we excluded several clinically relevant studies that may potentially induce implicit motor learning. An example is augmented error-learning. It has been found that patients with asymmetric gait walk more symmetrically after a practice period in which they walked with even larger step length asymmetry, namely on a split belt treadmill with both sides set at different speeds.[174,175] Indeed, as long as patients are not consciously aware of these artificially enhanced errors, this intervention may trigger them to implicitly adapt their step length. However, the opposite may also be true, in that enforced errors may actually enhance patients' awareness of their asymmetrical movement pattern, triggering them to explicitly correct it. The main point here is that without proper manipulation checks, we cannot tell which account holds true. Therefore, exclusion of studies that lacked these checks was warranted. A third limitation is the statistical heterogeneity that was present in most meta-analyses. Due to the limited number of studies we could often not further explore (i.e., by means of subgroup or meta-regression analysis) reasons for between-study variation in learning effect. In the two cases that exploration of heterogeneity was possible, we choose to group studies by lesion location, based on reports that some brain regions (like the subcortical basal ganglia[52,62]) may be more critical for implicit motor learning than others. Indeed, our decision to focus on this variable seems justified by the fact that lesion location indeed accounted for some of the statistical heterogeneity. However, our decision also meant that we were not in a position to further assess the possible role of other factors like studies' risk of bias score, patients' explicit knowledge, and duration of practice. A final limitation of this review concerns the risk of bias assessment. As of yet, there is no validated tool available to judge risk of bias in non-RCT's. Nonetheless, the use of a modified Newcastle-Ottawa Scale (NOS) used in this review is considered to be the best alternative.[100,176]

5. Conclusion

At this point, it remains unclear as to what degree implicit motor learning is possible after stroke. On a theoretical level, the application of implicit motor learning paradigms within rehabilitation practice post-stroke does still hold promise. Therefore, future research should focus on the effectiveness and feasibility of implicit motor learning in people with stroke, within clinically relevant contexts.

6. Acknowledgements

We would like to thank the medical information specialist Ralph de Vries of the medical library of the Vrije Universiteit Amsterdam for optimizing the search strategy.

Appendix 3.1. Search Strategy.

Example of the search strategy for Medline.

#1	(Implicit*[tiab] OR procedural*[tiab] OR sequen*[tiab] OR unintentional*[tiab] OR incidental*[tiab] OR nondeclarative[tiab] OR non declarative[tiab] OR analogy[tiab] OR errorless[tiab] OR dual task[tiab] OR external focus[tiab] OR Implicit*[ot] OR procedural*[ot] OR sequen*[ot] OR unintentional*[ot] OR incidental*[ot] OR nondeclarative[ot] OR non declarative[ot] OR analogy[ot] OR errorless[ot] OR dual task[ot] OR external focus[ot])
#2	("Learning"[Mesh] OR Learn*[tiab] OR Learn*[ot])
#3	(memory[tiab] OR knowledge[tiab] OR memory[ot] OR knowledge[ot])
#4	("Psychomotor Performance"[Mesh] OR Psychomotor*[tiab] OR Motor*[tiab] OR Task perform*[tiab] OR Task sequen*[tiab] OR Reaction time*[tiab] OR Psychomotor*[ot] OR Motor*[ot] OR Task perform*[ot] OR Task sequen*[ot] OR Reaction time*[ot]))
#5	((("Stroke"[Mesh] OR cva[tiab] OR cvas[tiab] OR poststroke*[tiab] OR stroke*[tiab] OR apoplex*[tiab]) OR (brain*[tiab] OR cerebr*[tiab] OR cerebell*[tiab] OR intracran*[tiab] OR intracerebral*[tiab] OR vertebrobasilar*[tiab]) AND vascular*[tiab] AND (disease[tiab] OR diseases[tiab] OR accident*[tiab] OR disorder*[tiab])) OR (cerebrovascular*[tiab] AND (disease[tiab] OR diseases[tiab] OR accident*[tiab] OR disorder*[tiab])) OR ((brain*[tiab] OR cerebr*[tiab] OR cerebell*[tiab] OR intracran*[tiab] OR intracerebral*[tiab] OR vertebrobasilar*[tiab]) AND (haemorrhag*[tiab] OR hemorrhag*[tiab] OR ischemi*[tiab] OR ischaemi*[tiab] OR infarct*[tiab] OR haematoma*[tiab] OR hematoma*[tiab] OR bleed*[tiab])) OR ("Hemiplegia"[Mesh] OR "Paresis"[Mesh] OR hemipleg*[tiab] OR hemipar*[tiab] OR paresis[tiab] OR paretic[tiab])) OR ("Brain Injuries"[Mesh] OR brain injur*[tiab] OR brain trauma*[tiab] OR brain lesion*[tiab] OR brain laceration*[tiab] OR brain contusion*[tiab] OR brain damage[tiab] OR concussion*[tiab] OR cerebral injur*[tiab] OR cerebral trauma*[tiab] OR cerebral lesion*[tiab] OR cerebral laceration*[tiab] OR cerebral contusion*[tiab] OR cerebral damage[tiab] OR repeated head trauma[tiab] OR repetitive head trauma[tiab] OR traumatic encephalopath*[tiab] OR tbi[tiab] OR tbis[tiab] OR ctbi-b[tiab] OR contrecoup[tiab] OR post-concussi*[tiab] OR postconcussi*[tiab] OR post-trauma*[tiab] OR posttrauma*[tiab] OR traumatic brain*[tiab] OR traumatic midbrain*[tiab] OR traumatic cerebellar*[tiab] OR traumatic intracerebellar*[tiab] OR traumatic intra-cerebellar*[tiab] OR traumatic cerebral*[tiab] OR traumatic intracerebral*[tiab] OR traumatic intra-cerebral*[tiab] OR axonal injur*[tiab] OR dai[tiab] OR dais[tiab] OR traumatic epileps*[tiab] OR impact seizure*[tiab] OR concussive convulsion*[tiab] OR commotio cerebri[tiab] OR ((prefrontal[tiab] OR frontal[tiab] OR basal ganglia[tiab] OR striat*[tiab] OR parietal[tiab] OR cerebel*[tiab]) AND (lesion*[tiab] OR damag*[tiab]))))
#6	((#1 AND (#2 OR #3)) AND # 4 AND 5#) NOT ("Animals"[Mesh] NOT "Humans"[Mesh])

Appendix 3.2. Modified Newcastle Ottawa Scales.

The three different Newcastle Ottawa Scales used to assess studies' risk of bias for each of the three research questions. Of note, for each NOS-scale the items on performance bias rated studies' quality on their success of blinding participants (i.e., the amount of explicit knowledge that participants gained with practice). In the NOS-scales used in this study, these items were given extra weight (i.e., 2 points could be scored per item, instead of 1), as it is the hallmark of implicit motor learning that learners do not gain explicit movement-related knowledge. Studies in which learners gained considerable explicit knowledge run the risk of having measured a more explicit form of motor learning.

NOS - version 1: Tool to assess risk of bias of studies for research question 1: Can patients with stroke learn motor tasks implicitly?

Selection

1) Representativeness of patient group
- One star was awarded when in- and exclusion criteria and patient characteristics were described (i.e., diagnosis, lesion location, time post-stroke, and motor and cognitive abilities)

2) Selection of patient group
- Studies that provided a detailed description of the recruitment of patients were awarded a star. (Where were patients included, how many patients were screened, and how many of them eventually participated?)

Performance bias

3) Blinding of patients (check of explicit knowledge)
- Stars were awarded if patients' explicit knowledge of the learned motor task was comprehensively tested and reported. Thus, for SRT-type tasks, one star was awarded if at least a recognition or recall test was administered. Optionally, two stars could be awarded if both these tests were used. For complex motor tasks, one star was awarded if the number of verbal movement related rules was assessed

4) Blinding of patients (explicit knowledge results)
- Stars were awarded if blinding of participants' was proven successful. That is, if the results of the explicit knowledge tests indicated that patients did not accumulate explicit knowledge. Thus, for SRT-type tasks, two stars were awarded if recognition/recall scores were not above chance levels. For complex motor tasks, two stars were awarded if significantly fewer verbal movement related rules were reported by the implicit group than by the explicit group

Outcome

5) Was follow-up long enough for outcomes to occur?
- One star was awarded if a separate retention test was included (>24 hours post-practice)

6) Follow-up adequacy
- One star was awarded if ≤ 10% of the subjects was lost to follow-up

NOS-version 2: Tool to assess risk of bias of studies for research question 2: Is implicit motor learning of patients impaired compared to healthy peers?

Selection

1) Representativeness of patient group
- One star was awarded when in- and exclusion criteria and patient characteristics were described (i.e., diagnosis, lesion location, time post-stroke, and motor and cognitive abilities)

2) Selection of patient group
- Studies that provided a detailed description of the recruitment of patients were awarded a star. (Where were patients included, how many patients were screened, and how many of them eventually participated?)

3) Selection of control group
- Studies that selected control subjects from the same community as the stroke patient group were awarded a star

Performance bias

4) Blinding of participants (check of explicit knowledge)
- Stars were awarded if patients' explicit knowledge of the learned motor task was comprehensively tested and reported. Thus, for SRT-type tasks, one star was awarded if at least a recognition or recall test was administered. Optionally, two stars could be awarded if both these tests were used. For complex motor tasks, one star was awarded if the number of verbal movement related rules was assessed

5) Blinding of participants (explicit knowledge results)
- Stars were awarded if blinding of participants' was proven successful. That is, if the results of the explicit knowledge tests indicated that patients did not accumulate explicit knowledge. Thus, for SRT-type tasks, two stars were awarded if recognition/recall scores were not above chance levels. For complex motor tasks, two stars were awarded if significantly fewer verbal movement related rules were reported by the implicit group than by the explicit group

Comparability

6) Comparability of groups (1)
- One star was awarded when possible confounders were reported. At least the following information should be obtained: age, motor functioning, and cognitive functioning/education level

7) Comparability of groups (2)
- One star was awarded when groups were matched with regard to possible confounders or if confounders were statistically corrected for. At least 2 of the following 3 confounders should be taken into account: Age, motor functioning, and cognitive functioning/education level

8) Comparability of groups (3)
- One star was awarded when the amount of explicit knowledge was similar for patient and control groups. Alternatively, one star was awarded if follow-up analyses revealed that differences in explicit knowledge could not explain differences in learning between groups

Outcome

9) Was follow-up long enough for outcomes to occur?
- One star was awarded if a separate retention test was included (>24 hours post-practice)

10) Follow-up adequacy
- One star was awarded if ≤ 10% of the subjects was lost to follow-up

NOS-version 3: Tool to assess risk of bias of studies for research question 3: Is implicit motor learning more or less impaired than explicit motor learning following stroke?

Selection

1) Representativeness of patient group
- One star was awarded when in- and exclusion criteria and patient characteristics were described (i.e., diagnosis, lesion location, time post-stroke, and motor and cognitive abilities)

2) Selection of implicit stroke group
- Studies that provided a detailed description of the recruitment of patients were awarded a star. (Where were patients included, how many patients were screened, and how many of them eventually participated?)

3) Selection of explicit stroke group
- Studies that selected patients of the explicit group from the same community as those from the implicit group were awarded a star

Performance bias

4) Blinding of participants (check of explicit knowledge)
- Stars were awarded if patients' explicit knowledge of the learned motor task was comprehensively tested and reported. Thus, for SRT-type tasks, one star was awarded if at least a recognition or recall test was administered. Optionally, two stars could be awarded if both these tests were used. For complex motor tasks, one star was awarded if the number of verbal movement related rules was assessed

5) Blinding of participants (explicit knowledge results)
- Stars were awarded if blinding of participants' was proven successful. That is, if the results of the explicit knowledge tests indicated that patients did not accumulate explicit knowledge. Thus, for SRT-type tasks, two stars were awarded if recognition/recall scores were not above chance levels. For complex motor tasks, two stars were awarded if significantly fewer verbal movement related rules were reported by the implicit group than by the explicit group

Comparability

6) Comparability of groups (1)

- One star was awarded when possible confounders were reported. At least the following information should be obtained: age, motor functioning, cognitive functioning/education level, and lesion location

7) Comparability of groups (2)

- One star was awarded when groups were matched with regard to possible confounders or if confounders were statistically corrected for. Besides lesion location and time since stroke, at least 2 of the following 3 confounders should be taken into account: Age, motor functioning, and cognitive functioning/education level

8) Comparability of groups (3)

- One star was awarded when the explicit group gained more explicit knowledge than the implicit group

Outcome

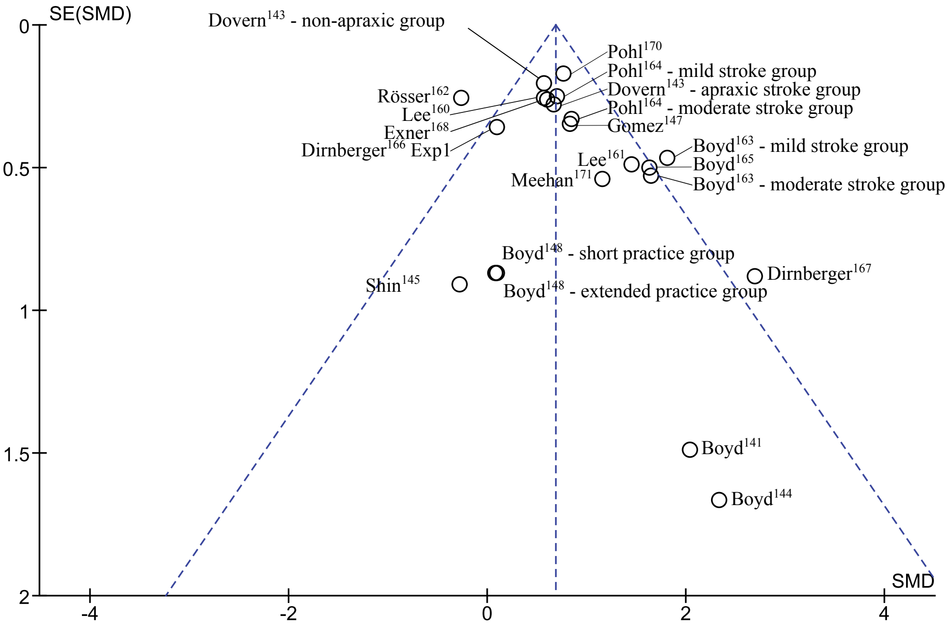
9) Was follow-up long enough for outcomes to occur?

- One star was awarded if a separate retention test was included (>24 hours post-practice)

10) Follow-up adequacy

- One star was awarded if ≤ 10% of the subjects was lost to follow-up

Appendix 3.3. Funnel plot of included studies.



NB: Studies were pooled for the main research question ("Can patients with stroke learn motor tasks implicitly?"). For each study, its effect estimate (standard mean difference of performance in random versus repeated block; SMD) is plotted against its precision (standard error of the SMD; SE). The symmetrical distribution of studies suggests that no publication bias was present.

Appendix 3.4. Study Characteristics.

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Boyd & Winstein[148] - Stroke group (Implicit learning – short practice) - Stroke group (Implicit learning- extended practice) - Stroke group (Explicit learning– short practice)	Stroke: - ≥ 6 months since stroke - Unilateral damage to sensorimotor brain areas	Stroke (implicit – short practice): - *N* (m/f) = 4 (3/1) - Age (y) = 54 ± 16 - Months since stroke = 60 ± 45 - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = (3/1) - MMSE = 28.0 ± 0.8 - Motor functioning = ? Stroke (implicit - extended practice) - *N* (m/f) = 4 (4/0) - Age (y) = 59 ± 14 - Months since stroke = 7 ± 1 - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = (3/1) - MMSE = 28.3 ± 1.1 - Motor functioning = ? Stroke (explicit – short practice) - *N* (m/f) = 4 (2/2) - Age (y) = 55 ± 4 - Months since stroke = 13 ± 7 - Stroke location = (sub)cortical-SupT (3) & Pons (1) - Lesion side (L/R) = SMC(3/0)/Pons(0/1) - MMSE = 27.8 ± 1.5 - Motor functioning = ?	SRT task Procedure: Block = 6 repetitions of 9-item sequence **Day 1** 6 blocks: - Blocks 1 & 5: random - Blocks 2-4 & 6: repeated For the extended practice group, the above procedure was repeated on day 2 and day 3 Hand used: Ipsilesional hand	Average median response time (ms) per block Implicit motor learning: Mean difference in reaction time between block 5 (random) and 6 (repeated) at the last day of practice	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Recall (% correct) - Chance = 25%) **Results:** Stroke (implicit – short practice): Aware = 25% Recognition = 0% Recall = 8% ± 14 Stroke (implicit - extended practice): Aware = 0% Recognition = 0% Recall = 17% ± 17 Stroke (explicit – short practice): Recognition = 100% Recall = 50% ± 29

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Boyd & Winstein[141] - Stroke group (Implicit learning) - Stroke group (Explicit learning) - Control group (Implicit learning) - Control group (Explicit learning)	<u>Stroke:</u> - ≥ 6 months since stroke - Unilateral damage to sensorimotor cortex (MCA) - Right hand dominant - MMSE > 25 - No acute medical problems - No uncorrected visual impairment - No history of psychiatric admission, or neurologic impairment <u>Control:</u> - Same criteria + no neurological impairment	<u>Stroke (Implicit):</u> - *N* (m/f) = 5 (4/1) - Age (y) = 59 ± 19 - Months since stroke = 48 ± 30 - Stroke location = Cortical-MCA - Lesion side (L/R) = 4/1 - MMSE = 27.8 ± 1.8 - FMA-UE (0-66) = 27 ± 19 <u>Stroke (Explicit):</u> - *N* (m/f) = 5 (2/3) - Age (y) = 59 ± 11 - Months since stroke = 33 ± 19 - Stroke location = Cortical-MCA - Lesion side (L/R) = 2/3 - MMSE = 29.0 ± 1.2 - FMA-UE (0-66) = 30 ± 21 <u>Control (Implicit):</u> - *N* (m/f) = 5 (2/3) - Age (y) = 57 ± 16 - MMSE = 29.6 ± 0.5 <u>Control (Explicit):</u> - *N* (m/f) = 5 (1/4) - Age (y) = 55 ± 11 - MMSE = 29.8 ± 0.4	SRT task <u>Procedure:</u> Block = 10 repetitions of 10-item sequence **Days 1-3:** 7 blocks: - Blocks 1 & 6: random - Blocks 2-5 & 7: repeated **Day 4:** - 1 repeated & 1 random block <u>Hand used:</u> Stroke: ipsilesional hand Control: matched to stroke groups	Average median response time (ms) per block <u>Implicit motor learning:</u> Mean difference in response time between the repeated block at retention and the random block at end of day 1	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 50% - Recall (% correct) - Chance = 50% **Results:** <u>Stroke (Implicit):</u> Aware = 20% Recognition = 53% Recall = 33% <u>Stroke (Explicit):</u> Recognition = 73% Recall = 53% <u>Control (Implicit):</u> Aware = 80% Recognition = 66% Recall = 40% <u>Control (Explicit):</u> Recognition = 100% Recall = 86%

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Boyd & Winstein[144] - Stroke group (Implicit learning) - Stroke group (Explicit learning) - Control group (Implicit learning) - Control group (Explicit learning)	Stroke: - ≥ 6 months since stroke - Unilateral BG damage - Right hand dominant - MMSE > 25 - No acute medical problems - No uncorrected visual impairment - No history of psychiatric admission, or neurologic impairment Control: - Same criteria + no neurological impairment	Stroke (Implicit): - *N* (m/f) = 5 (3/2) - Age (y) = 58 ± 15 - Months since stroke = 10 ± 6 - Stroke location = Subcortical-BG - Lesion side (L/R) = 1/4 - MMSE = 28.4 ± 1.1 - FMA-UE (0-66) = 44 ± 16 Stroke (Explicit): - *N* (m/f) = 5 (4/1) - Age (y) = 51 ± 10 - Months since stroke = 28 ± 28 - Stroke location = Subcortical-BG - Lesion side (L/R) = 1/4 - MMSE = 28 ± 1.4 - FMA-UE (0-66) = 48 ± 20 Control (Implicit): - *N* (m/f) = 5 (2/3) - Age (y) = 57 ± 16 - MMSE = 29.6 ± 0.5 Control (Explicit): - *N* (m/f) = 5 (1/4) - Age (y) = 55 ± 11 - MMSE = 29.8 ± 0.4	CT task Procedure: Block = 10 trials of tracking (30 seconds) **Days 1-3:** - 5 blocks of tracking **Day 4:** - Retention test: 1 block of tracking Hand used: Stroke: ipsilesional hand Control: matched to stroke groups	Average root-mean-squared error (RMSE) of tracking for random and repeated segments per block Implicit motor learning: Mean difference in RMSE during tracking of repeated segments at retention and tracking of random segments at the end of day 1	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 50% - Recall (% correct) - Chance = 33% **Results:** Stroke (Implicit): Aware = 0% Recognition = 46% ± 15 Recall = 0% Stroke (Explicit): Recognition = 40% ± 28 Control (Implicit): Aware = 0% Recognition = 66% ± 33 Recall = 20% Control (Explicit): Recognition = 73% ± 33

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Boyd et al.[163] - Mild stroke group - Moderate stroke group - Control group	Stroke: - ≥ 6 months since stroke - Unilateral brain lesion - Right hand dominant - MMSE > 25 - No acute medical problems - No UE pathology - No uncorrected visual impairment - No history of psychiatric admission, or neurologic impairment Control: - No neurological impairment - Age-matched	Stroke (mild): - *N* (m/f) = 16 (10/6) - Age (y) = 54 ± 4 - Months since stroke = ? - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 9/7 - MMSE = 29.5 ± 0.8 - Motor functioning = ? - Orpington score = 2.3 ± 0.1 Stroke (moderate): - *N* (m/f) = 12 (5/7) - Age (y) = 61 ± 3 - Months since stroke = ? - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 5/7 - MMSE = 28.8 ± 1.2 - Motor functioning = ? - Orpington score =3.4 ± 0.2 Control: - *N* (m/f) = 17 (6/11) - Age (y) = 53 ± 3 - MMSE = 29.7 ± 0.7	SHM task SRT task Procedure: - SHM & SRT: Block = 10 repetitions of 10-item sequence **Day 1:** Both tasks: 12 blocks - Block 1 & 11: random - Blocks 2-10 & 12: repeated Hand used: Stroke: ipsilesional hand Control: matched to stroke groups	Both tasks: Average median response time (ms) per block Implicit motor learning: Both tasks: Mean difference in response time between (repeated) block 12 and (random) block 11	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 50% - Recall (% correct) - Chance = 25% **Results:** Stroke (Mild): SHM: Aware = 81% SHM: Recognition = 64% ± 30 SHM: Recall = 57% ± 14 SRT: Aware = 56% SRT: Recognition = 64% ± 12 SRT: Recall = 51% ± 19 Stroke (Moderate): SHM: Aware = 85% SHM: Recognition = 72% ± 15 SHM: Recall = 44% ± 22 SRT: Aware = 62% SRT: Recognition = 56% ± 21 SRT: Recall = 37% ± 15 Control: SHM: Aware = 82% SHM: Recognition = 81% ± 16 SHM: Recall = 69% ± 17 SRT: Aware = 71% SRT: Recognition = 66% ± 19 SRT: Recall = 59% ± 22

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Boyd et al.[165] - Stroke group - Control group	<u>Stroke:</u> - ≥ 6 months since stroke - Damage to BG - MMSE > 25th percentile - No uncorrected visual impairment - No orthopedic condition interfering with task performance <u>Control:</u> - Same criteria + no neurological impairment	<u>Stroke:</u> - *N* (m/f) = 13 (8/5) - Age (y) = 59 ± 16 - Months since stroke = 60 ± 53 - Stroke location = Subcortical-BG - Lesion side (L/R) = 2/11 - MMSE = 28.3 ± 2 - FMA-UE (0-66) = 34 ± 18 - Orpington score = 2.8 ± 0.7 <u>Control:</u> - *N* (m/f) = 13 (5/8) - Age (y) = 60 ± 16 - MMSE = 29.8 ± 0.6	SRT task <u>Procedure:</u> Block = 10 repetitions of 12-item sequence **Days 1&2** 6 blocks: - Block 1: random - Blocks 2-6: repeated **Day 3:** - Retention test: 1 repeated block <u>Hand used:</u> Stroke: ipsilesional hand Control: matched to stroke group	Average median response time (ms) per block <u>Implicit motor learning:</u> Mean difference in response time between repeated block at retention, and last random block on day 2	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 50% - Recall (% correct) - Chance = 25% **Results:** <u>Stroke:</u> Aware = 85% Recognition-true = 67% ± 41 Recognition-false = 68% ± 30 Recall = 52% ± 20 <u>Control:</u> Aware = 77% Recognition-true = 82% ± 22 Recognition-false = 83% ± 21 Recall = 52% ± 16

Author / Experimental groups	**Inclusion criteria**	**Group characteristics**	**Motor task**	**Outcome measure**	**Declarative knowledge**
Dirnberger et al. (Exp. 1)[166] - Stroke group - Control group	Stroke: - > 6 months since stroke - Isolated cerebellar lesion - No other cerebral pathology - No history of neurological, psychiatric, or other relevant disease (e.g., arthritis) Control: - No neurological impairment	Stroke: - *N* (m/f) = 11 (5/6) - Age (y) = 46 ± 15 - Months since stroke = 31 ± 18 - Stroke location = CB - Lesion side (L/R/Bilateral) = 3/4/4 - MMSE = 29 ± 1 - ICARS = 6 ± 4 - PP (UL/UR/BL/BR) = 13±2/12±3/9±2/10±2 Control: - *N* (m/f) = 13 (6/7) - Age (y) = 45 ± 14 - MMSE = 29 ± 1 - PP (UL/UR/BL/BR) = 14±2/15±2/11±2/12±2	SRT task Procedure: Block = 9 repetitions of 10-item sequences **Day 1:** 3 runs of 14 blocks: - Blocks 1&2: random - Blocks 3-7: repeated - Blocks 8&9: random - Blocks 10-14: interference Followed by: - 2 random & 5 repeated blocks Hand used: Stroke & Control: Middle and index finger of each hand	Average median response time (ms) per block Implicit motor learning: Mean difference in response time between final 5th repeated block and last preceding random block[a] at retention	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 33% - Recall (# items) **Results:** Stroke: Awareness = 46% Control: Awareness = 62% Both groups - Recognition & recall: "No participant could recall the sequence, and both groups performed at chance when asked to identify the sequence out of three alternatives" (p. 1205)

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Dirnberger et al.[167] - Stroke group - Control group	Stroke: - > 6 months since stroke - Isolated cerebellar lesion - No other cerebral pathology - No history of neurological or psychiatric disease Control: - No neurological impairment	Stroke: - *N* (m/f) = 10 (5/5) - Age (y) = 47 ± 15 - Months since stroke = 28 ± 16 - Stroke location = CB - Lesion side (L/R/Bilateral) = 3/4/3 - MMSE = 29 ± 1 - Motor functioning = ? Control: - *N* (m/f) = 13 (7/5) - Age (y) = 43 ± 14 - MMSE = 29 ± 1 - Motor functioning = ?	SRT task Procedure: - Repeated/Test block = 45 repetitions of 10-item sequence - Random block = 9 repetitions of random 10-item sequence **Day 1:** 4 runs of 4 blocks: - Block 1: random - Block 2: repeated - Block 3: random - Block 4: test Hand used: Stroke & Control: Middle and index finger of each hand	Average median response time (ms) per block Implicit motor learning: Mean difference in response time between final repeated block (in run 4) and subsequent random block	**Tests used:** - Awareness (% of participants) - Recognition (% correct) - Chance = 33% - Recall (# items) **Results:** Stroke: Aware = 50% Recognition = 50% Control: Aware = 58% Recognition = 33% Both groups – Recall: "No participant could recall the sequence …" (p. 2212)

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Dovern et al.[143] - Apraxic stroke group - Non-apraxic stroke group - Control group	<u>Stroke:</u> - First-ever left MCA-stroke - > 8 days since stroke - Right hand dominant - For apraxic patients: Impaired in: imitating meaningless hand/finger positions, or imitating/ actual object-use <u>Control:</u> - Healthy - Age-matched	<u>Stroke (apraxic):</u> - *N* (m/f) = 18 (9/9) - Age (y) = 57 ± 12 - Days since stroke = 367 [16-1209] - Stroke location =(sub)cortical-MCA - Lesion side (L/R) = 18/0 - WM (CBTT) = 4.8 - ARAT (0-57) = 30 <u>Stroke (non-apraxic):</u> - *N* (m/f) = 30 (22/8) - Age (y) = 50 ± 12 - Days since stroke = 315 [27-1506] - Stroke location =(sub)cortical-MCA - Lesion side (L/R) = 30/0 - WM (CBTT) = 5.3 - ARAT (0-57) = 42 <u>Control:</u> - *N* (m/f) = 17 (8/9) - Age (y) = 54 ± 10 - WM (CBTT) = 5.4	SRT task <u>Procedure:</u> Block = 10 repetitions of 6-item sequence **Day 1:** 5 blocks: - Blocks 1-4: repeated - Block 5: different sequence with equal stimulus(-transition) probabilities as practiced sequence <u>Hand used:</u> Stroke & Control: left hand (ipsilesional/non-dominant hand)	Average median response time (ms) per block <u>Implicit motor learning:</u> Mean difference in response time between block 4 (repeated) and block 5 (random/unpracticed)	**Tests used:** - Awareness (% of participants) - Recall (# items) **Results:** <u>Stroke (apraxic):</u> Recall = 2.7 ± 2.1 items <u>Stroke (non-apraxic):</u> Recall = 3.4 ± 2.0 items <u>Control:</u> Recall = 4.4 ± 1.3 items

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Exner et al.[168] - Stroke group - Control group	Stroke: - Isolated BG-lesions - ≥ 6 months since stroke - < 70 years - No history of psychiatric or neurological impairment Control: - No neurological impairment - Matched for age, sex, & years of education	Stroke: - *N* (m/f) = 20 (17/3) - Age (y) = 53 ± 11 - Months since stroke = 24 ± 1.5 - Stroke location = Subcortical-BG - Lesion side (L/R/Bilateral) = 9/9/2 - WAIS-R (IQ) = 100 ± 18 - General incoordination (no/mild/moderate) = 14/3/3 Control: - *N* (m/f) = 20 (15/5) - Age (y) = 52 ± 9 - WAIS-R (IQ) = 111 ± 18 - Motor functioning = ?	SRT task Procedure: Block = 10 repetitions of 12-item sequence **Day 1:** 8 blocks: - Blocks 1 & 6: random - Block 2-5 & 7-8: repeated Hand used: Stroke & Control: middle and index finger of both hands	Average response time (ms) per block Implicit motor learning: Mean difference in response time between block 5 (repeated) and block 6 (random)	**Tests used:** - Recall (# items) **Results:** Both groups: "None of the groups scored significantly above random level" (p. 379)

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Gómez-Beldarrain et al.[147] - Stroke group - Control group	Stroke: - Isolated CB-lesions - ≥ 6 months since stroke - Right hand dominant - No history of cognitive or neurological impairment Control: - No neuro(psycho)logical or physical impairment - Not using any medication	Stroke: - N (m/f) = 14 (10/4) - Age (y) = 61 ± 11 - Months since stroke = 29 ± 22 - Stroke location = CB - Lesion side (L/R) = 9/5 - WAIS-R (IQ) = N/A - PP (UL/UR) = 11/12 Control: - N (m/f) = 10 (7/3) - Age (y)[range] = 62.6 [52-72] - WAIS-R (IQ) = N/A - PP (UL/UR) = 12/13.9	SRT task Procedure: Block = 10 repetitions of 10-item sequence **Day 1:** 5 blocks: - Blocks 1&5: random - Block 2-4: repeated Hand used: Stroke & Control: Both hands tested separately	Median response time (ms) per block Implicit motor learning: Mean difference in response time between block 4 (repeated) and block 5 (random)	**Tests used:** - Awareness (% of participants) **Results:** Stroke: Aware = 0% Control: Aware = 20% "None of the patients achieved explicit knowledge of the sequence and only two controls mentioned having noticed some sort of sequence, but were unable to reproduce the numbers" (p. 28)
Lee et al.[160] - Stroke group - Control group	Stroke: - Unilateral brain damage - Korean MMSE > 24 - No hemianopsia/ unilateral spatial neglect - Right hand dominant Control: - No neurological impairment	Stroke: - N (m/f) = 20 (12/8) - Age (y) = 58 ± 12 - Months since stroke = 3.9 ± 2.6 - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 8/12 - Korean MMSE = 27.1 ± 1.9 - Motor functioning = ? Control: - N (m/f) = 20 (11/9) - Age (y) = 57 ± 7 - Cognitive/motor functioning = ?	SRT task Procedure: Block = 10 repetitions of 10-item sequence **Day 1** 7 blocks: - Block 1&6: random - Block 2-5 & 7: repeated **Day 2** 3 retention blocks: - Blocks 1&3: random - Block 2: repeated Hand used: Stroke: ipsilesional hand Control: matched to stroke group	Average response time (ms) per block Implicit motor learning: Mean difference in response time between block 2 (repeated) and block 3 (random) at retention	**Tests used:** - Awareness (% of participants) **Results:** Stroke: Aware = 35% Control: Aware = 60% Authors state that no subject could recall the exact order of stimuli (p.30-31)

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Lee et al.[161] - Stroke group - Control group	Stroke: - Unilateral brain damage - < 3 months after stroke - Korean MMSE > 24 - No hemianopsia, or unilateral spatial neglect - Right hand dominant Control: - No neurological impairment	Stroke: - *N* (m/f) = 12 (7/5) - Age (y) = 62 ± 12 - Months since stroke = 1.9 ± 0.2 - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 5/7 - Korean MMSE = 26.7 ± 0.4 - Motor functioning = ? Control: - *N* (m/f) = 12 (7/5) - Age (y) = 57 ± 7 - Cognitive/motor functioning = ?	SRT task Procedure: Block = 10 repetitions of 12-item sequence **Day 1** 7 blocks: - Blocks 1&6: random - Block 2-5 & 7: repeated Hand used: Stroke: ipsilesional hand Control: matched to stroke group	Average response time (ms) per block Implicit motor learning: Mean difference in response time between block 5 (repeated) and block 6 (random)	**Tests used:** - Awareness (% of participants) **Results:** Stroke: Aware = 33% Control: Aware = 67% [Authors state that no subject could recall the exact order of stimuli (p. 4)]
Meehan et al.[171] - Stroke group - Control group	Stroke: - ≥ 12 months since stroke - Subcortical stroke - Right hand dominant - MMSE > 25th percentile - No earlier stroke - No psychiatric, neurologic, orthopedic or uncorrected visual impairment Control: - No neurological impairment - Age- and sex-matched	Stroke: - *N* (m/f) = 9 (6/3) - Age (y) = 64 ± 6 - Months since stroke = 53 ± 47 - Stroke location = Subcortical-SupT - Lesion side (L/R) = 0/9 - MMSE = 29.3 ± 0.7 - FMA-UE (0-66) = 54 ± 12 Control: - *N* (m/f) = 9 (4/5) - Age (y) = 63 ± 7 - MMSE = 29.7 ± 0.5 - Motor functioning = ?	CT task Procedure: Block = 10 trials of tracking (20 s) **Day 1**: - 1 random & 1 repeated block **Days 2-6:** 5 blocks **Day 7:** Same as day 1 Hand used: Stroke: contralesional hand Control: left (non-dominant) hand	Average root-mean-squared error (RMSE) of tracking for random and repeated segments for each block Implicit motor learning: Mean difference in RMSE for repeated and random segments at retention (day 7)	**Tests used:** - Recognition (%) - Chance = 50% **Results:** Stroke: Recognition = 54% Control: Recognition = 53%

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Orrell et al.[75] - Stroke group (Implicit/errorless learning) - Stroke group (Explicit/discovery learning) - Control group (Implicit/errorless learning) - Control group (Explicit/discovery learning)	<u>Stroke:</u> - ≥ 12 months since stroke - First-ever stroke - MMSE > 24 - Discharged from all rehabilitation services <u>Control:</u> - No neurological impairment	<u>Stroke (errorless):</u> - *N* (m/f) = 5 (4/1) - Age (y) = 49 ± 16 - Months since stroke = ? - Stroke location & side = (sub)cortical-SupT = 4(2L/2R), CB=1 - MMSE = 26.8 ± 0.8 - BBS (0-56) = 38 ± 5.8 <u>Stroke (discovery):</u> - *N* (m/f) = 5 (5/0) - Age (y) = 55 ± 12 - Months since stroke = ? - Stroke location = (sub)cortical-SupT - Lesion side (L/R/Bilateral) = 1/3/1 - MMSE = 25.8 ± 1.3 - BBS (0-56) = 38 ± 9 <u>Control (errorless):</u> - *N* (m/f) = 6 (3/3) - Age (y) = 67 ± 9 - MMSE = 29.2 ± 0.7 - BBS (0-56) = 52 ± 1 <u>Control (discovery):</u> - *N* (m/f) = 6 (3/3) - Age (y) = 63 ± 5 - MMSE = 29.3 ± 0.78 - BBS (0-56) = 54 ± 1	Balance task: <u>Errorless learning:</u> Task difficulty progressively increased throughout practice <u>Discovery learning:</u> Task difficulty similar across trials; Participants need to discover verbal rules of how to perform task <u>Procedure:</u> Block = 1 trial of 60 seconds of balancing on balance board **Day 1** (acquisition + post-test) - 24 repeated blocks - 4 blocks: ST-performance - 4 blocks: DT-performance (kettle lift/ number recall) **Day 8** (delayed retention): - 2 blocks ST-performance	Deviation from horizontal axis, expressed as average root-mean-squared error (RMSE) <u>Implicit motor learning:</u> Balance performance at delayed retention test	**Tests used:** - # verbal movement-related rules **Results:** <u>Stroke (errorless):</u> Number of rules: 1.4 ± 1.1 <u>Stroke (discovery):</u> Number of rules: 3.4 ± 1.3 <u>Control (errorless):</u> Number of rules: 1.8 ± 0.8 <u>Control (discovery):</u> Number of rules: 2.7 ± 1.0

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Orrell al.[169] - Stroke group - Control group	Stroke: - ≥ 12 months since stroke - Hemiparesis - Able to understand instructions - MMSE > 24 - Discharged from all rehabilitation services - No hemianopsia or orthopedic impairment Control: - No neurological impairment	Stroke: - *N* (m/f) = 7 (2/5) - Age (y) = 60 ± 10 - Months since stroke = 35 ± 13 - Stroke location = (sub)cortical-AC - Lesion side (L/R) = 0/7 - MMSE = 26.3 ± 1.0 - General motor impairment level (0-14) = 5.3 ± 2.4 Control: - *N* (m/f) = 9 (4/5) - Age (y) = 47 ± 9 - MMSE = 29.1 ± 1.1 - Motor functioning = ?	SRT task Procedure: Block = 10 repetitions of 12-item sequence **Days 1&2** (acquisition): - Blocks 1-17 & 19-20: repeated - Block 18: random **Day 2** (transfer task): - 2 random & 2 repeated blocks **Day 16** (delayed retention) - SRT: 6 repeated blocks - Transfer: 2 repeated & 2 random blocks Hand used: Stroke: Ipsilesional hand Control: Right hand	Median response time (ms) per block Implicit motor learning: Mean difference in response time between block 17 (repeated) and block 18 (random) at end of acquisition phase on day 2	**Tests used:** - Awareness (% of participants) - Recall/Prediction (# errors) - Chance = 90 errors/30 correct **Results:** Aware = ? Stroke: Recall = 47 errors ± 10 [i.e., 73 correct responses] Control: Recall = 27 errors ± 9 [i.e., 93 correct responses]

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Pohl et al.[170] - Stroke group - Control group	Stroke: - ≥ 60 years old - > 6 months since stroke - Stroke affecting AC - Community-dwelling - Right hand dominant - MMSE > 17 - Able to sit independently - No upper extremity impairment - No uncorrected visual impairment - No apraxia Control: - Same criteria + no neurological impairment	Stroke: - *N* (m/f) = 47 (29/18) - Age (y) = 71 ± 6 - Months since stroke = 43 ± 61 - Stroke location = (sub)cortical-AC - Lesion side (L/R) = ? - MMSE = 27.5 - Motor functioning = ? - General level of impairment Orpington: - 18 patients: mild (< 3.2) - 9 patients: moderate (3.2-5.2) - 20 patients: ? Control: - *N* (m/f) = 36 (15/21) - Age (y) = 73 ± 6 - MMSE = 28.6	SHM task Procedure: Block = 10 repetitions of 8-item sequence **Day 1** (practice) - Blocks 1 & 5-6: random - Blocks 2-4 & 7-8: repeated **Day 2** (retention) - 2 repeated blocks Hand used: Stroke: ipsilesional hand Control: matched to stroke group	Mean response (ms) time per block Implicit motor learning: Mean difference in response time between block 4 (repeated) and 5 (random) at end of practice	**Tests used:** - Awareness (% of participants) - Recall (# items) **Results:** Stroke: Aware = 68% Recall = 2.8 items ± 2.7 Control: Aware = 75% Recall = 2.4 items ± 1.8

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Pohl et al.[164] - Mild stroke group - Moderate stroke group - Control group	Stroke: - ≥ 50 years old - 30-150 days since stroke - No pre-existing disability - Community dwelling - Right hand dominant - MMSE > 23 - Able to sit independently - Orpington score ≤ 5.2 - No uncorrected visual impairment - No apraxia Control: - No history of neurologic impairment - Right hand dominant	Stroke (mild): - *N* (m/f) = 22 (13/9) - Age (y) = 72 ± 9 - Months since stroke = ? - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 13/9 - MMSE = 28.6 ± 2 - FAS (0-30) = 28 ± 2 - Orpington score < 3.2 Stroke (moderate): - *N* (m/f) = 15 (5/10) - Age (y) = 74 ± 9 - Months since stroke = ? - Stroke location = (sub)cortical-SupT - Lesion location (L/R) = 6/9 - MMSE = 26.6 ± 2.1 - FAS (0-30) = 27 ± 5 - Orpington: 3.2-5.2 Control: - *N* (m/f) = 30 (5/25) - Age (y) = 76 ± 7 - MMSE = 28.8 ± 1.3 - FAS (0-30) = 28 ± 1	SHM task Procedure: Block = 10 repetitions of 8-item sequence **Day 1:** 8 blocks: - Blocks 1-2 & 5: random - Blocks 3-4 & 6: repeated Hand used: Stroke: ipsilesional hand Control: - 20 controls: right hand - 20 controls: left hand	Mean response time (ms) per block Implicit motor learning: Mean difference in response time between block 4 (repeated) and 5 (random)	**Tests used:** - Awareness (% of participants) - Recall (# items) **Results:** Stroke (mild): Aware = 55% Stroke (moderate): Aware = 47% Control: Aware = 47% All three groups combined: Recall: 1.7 ± 2.2 "There was no difference between groups in the number of responses of the repeated sequence that could be recalled" (p. 251)

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Rösser et al.[162] - Stroke group (levodopa placebo condition)	Stroke: - 50-80 years old - (Sub)cortical stroke - > 1 year since stroke - Initial MRC <2, but current MRC ≥ 4.5 - MMSE ≥ 27 - No untreated cardiac, metabolic, or psychiatric disease - No drug (ab)use - No hypersensitivity for levodopa/carbidopa	Stroke: - *N* (m/f) = 18 (13/5) - Age (y) = 66 ± 7 - Months since stroke = 40 ± 25 - Stroke location = (sub)cortical-SupT - Lesion side (L/R) = 11/7 - MMSE = 29.4 ± 0.6 - RMA-AS (0-15) = 12 ± 2	SRT task Procedure: Block = 500 keypresses with shorter and longer sequential elements intermixed with random ones (i.e., 85% repeated and 15% random per block) **Session 1:** 2 blocks (with levodopa-placebo) Hand used: Contralesional hand	Mean response (ms) time for random and sequenced items per block Implicit motor learning: Mean difference in response time between random and sequenced items in the second block (for the placebo condition)	**Tests used:** - Awareness (% of participants) **Results:** Aware: ?

Author / Experimental groups	Inclusion criteria	Group characteristics	Motor task	Outcome measure	Declarative knowledge
Shin et al.[145] - Stroke group - Control group	Stroke: - Unilateral BG-stroke Control: - No neurologic impairment - Age-matched	Stroke: - *N* (m/f) = 4 (3/1) - Age (y) = 65 ± 9 - Months since stroke = ? - Stroke location = Subcortical-BG - Lesion side (L/R) = 2/2 - MMSE = 26.8 ± 3.9 - Fast-tapping task (interval in ms): Contralesional hand = 240 ± 98 Ipsilesional hand = 203 ± 30 Control: - *N* (m/f) = 7 (5/2) - Age (y) = 68 ± 4 - MMSE = (all ≥ 29) - Fast-tapping task (interval in ms): Dominant hand = 171 ± 16	SRT task Procedure: Block = 7 repetitions of 8-item sequence **Day 1** 7 practice blocks: - Blocks 1-2: random, 3-7: repeated 3x4 post-test blocks - Blocks 1&4: repeated, 2-3 either: 1) random stimuli location 2) random interstimulus interval 3) phase-shift interstimulus interval Hand used: Stroke: Both hands tested separately Control: Dominant (right) hand	Median response time (ms) per block Implicit motor learning: Mean difference in response time between first repeated and subsequent random block in post-test no. 1 (random stimuli location; spatial learning test)[b]	**Tests used:** - Awareness (% of participants) - Recall (# items) **Results:** Stroke & Control Aware: ? Recall: all participants < 3 "None of the control participants or patients could correctly report parts of either sequence longer than two successive sequence elements." (p. 78)

Author / Experimental groups	**Inclusion criteria**	**Group characteristics**	**Motor task**	**Outcome measure**	**Declarative knowledge**
Vakil et al.[149] - Stroke group - Control group	Stroke: - Isolated BG-lesions - No previous head trauma, or neurological/ endocrine disease - No drug-use that could alter cognitive performance - No dementia Control: - Age- & education-matched - Right handed - No neurological impairment	Stroke: - *N* (m/f) = 16 (11/5) - Age (y) = 59 ± 11 - Months since stroke = 16 - Stroke location = Subcortical-BG - Lesion side (L/R) = 5/11 - Years of education = 11 ± 3 - Motor functioning = ? Control: - *N* (m/f) = 16 (7/9) - Age (y) = 58 ± 8 - Years of education = 12 ± 3 - Motor functioning = ?	SRT task Procedure: Block = 10 repetitions of 10-item sequence **Day 1** (practice): - Blocks 5: random - Blocks 1-4: repeated **Day 2** (retention): 1 repeated block Hand used: Stroke & Control: Middle and index finger of each hand	Median response time (ms) per block Implicit motor learning: Mean difference in response time between block 4 (repeated) and block 5 (random)	**Tests used:** - Recall/Prediction (# items) - Chance = 2.5 **Results:** Stroke: Recall = 6.1 ± 1.9 Control: Recall = 5.4 ± 1.9

NB: AC = Anterior circulation; ARAT = Action Research Arm Test; BG = Basal ganglia; BBS = Berg Balance Scale; CB = Cerebellum; CBTT = Corsi block tapping test; CT = Continuous tracking task; DT = Dual-task; FAS = Florida Apraxia Screen; FMA-UE = Upper extremity subscale of Fügl-Meyer Assessment; ICARS = International Cooperative Ataxia Rating Scale (motor impairment scale); MCA = Middle cerebral artery; MMSE = Mini-Mental State Examination; MRC = Medical Research Council scale for muscle strength; PP (UL/UR/BL/BR) = Purdue Pegboard (unilateral left hand score/unilateral right hand score/bilateral left hand score/ bilateral right hand score); RMA-AS = Rivermead Motor Assessment, arm section; SHM = Serial hand movement task SMC = Sensorimotor cortex; SRT = Serial reaction time task; ST = single-task; SupT = Supratentatorial; WAIS-R = Wechsler Adult Intelligence Scale – Revised; WM = working memory; # = number of;

[a] Two different random blocks were tested, Re and Rm. For the Re random blocks, each stimulus and transition between stimuli was of equal probability. For the Rm random blocks, stimulus (-transition) probability was the same as for the sequence learned in the practice blocks. We chose to only look at the difference in reaction times between the last Rm (and not Re) block and the final repeated sequence block, as this provides the most conservative measure of implicit motor learning;

[b] This test of spatial learning is actually the conventional test of implicit motor learning (i.e., difference in reaction time to random and sequenced stimuli);

Chapter 4

The inclination for conscious motor control after stroke: Validating the Movement-Specific Reinvestment Scale for use in inpatient stroke patients

Elmar Kal
Han Houdijk
Peter van der Wurff
Erny Groet
Coen van Bennekom
Erik Scherder
John van der Kamp

Disability and Rehabilitation. 2016;38(11):1097-1106

Abstract

Background: Stroke survivors are inclined to consciously control their movements, a phenomenon termed “reinvestment”. Preliminary evidence suggests reinvestment to impair patients’ motor recovery. To investigate this hypothesis, an instrument is needed that can reliably assess reinvestment post-stroke. Therefore, this study aimed to validate the Movement-Specific Reinvestment Scale within inpatient stroke patients.

Methods: One-hundred inpatient stroke patients (<1 year post-stroke) and 100 healthy peers completed the MSRS, which was translated to Dutch for the study purpose. To assess structural validity, confirmatory factor analysis determined whether the scale measures two latent constructs, as previously reported in healthy adults. Construct validity was determined by testing whether patients had higher reinvestment than controls. Reliability analyses entailed assessment of retest reliability (ICC), internal consistency (Cronbach’s alpha), and minimal detectable change.

Results: Both structural and construct validity of the MSRS were supported. Retest reliability and internal consistency indices were acceptable to good. The minimal detectable change was adequate on group level, but considerable on individual level.

Conclusions: The MSRS is a valid and reliable tool and suitable to assess the relationship between reinvestment and motor recovery in the first months post-stroke. Eventually, this may help therapists to individualise motor learning interventions based on patients’ reinvestment preferences.

1. Introduction

Many individuals with stroke feel they need to consciously control their movements in order to ensure successful movement execution. This phenomenon is termed 'reinvestment':[177] attempting to consciously control movements by reinvesting explicit movement-related knowledge. Patients' inclination to reinvest may in part be due to the nature of instructions and feedback they receive during rehabilitation therapy – often directing their attention to *how* they should execute their movements.[43,178] Also, deviant movement patterns due to motor impairments may trigger heightened self-consciousness after stroke.[179]

Accumulating evidence suggests that a strong tendency to reinvest may worsen rather than improve the motor abilities of patients with stroke. For instance, healthy adults who rely on conscious motor control demonstrate inferior motor performance and learning,[57] and are more susceptible to experience skill-breakdown in dual-task[86] and high-pressure situations[93] compared to people who do not (or to a lesser extent). Also, reinvestment has been associated with an increased risk of falling in healthy elderly.[180] In line with these findings, chronic community-dwelling patients with stroke who are more predisposed to reinvest exhibit greater functional impairments.[28] This has triggered Orrell and co-workers to speculate that heightened reinvestment may impair motor recovery post-stroke. However, as this relationship is merely correlative, the presumed causality still needs to be established (i.e., an alternative explanation would be that patients with more severe motor impairments are more strongly triggered to reinvest, but that this increased reinvestment in itself does not exacerbate these impairments). Gaining insight into the role of reinvestment in motor learning post-stroke may help therapists select appropriate motor learning interventions for individual patients. Specifically, it will help them decide whether they should reduce patients' reliance on conscious motor control – for instance by the use of implicit motor learning strategies like errorless learning[107] or analogy learning[54] – or, alternatively, whether they should tune in to patients' preferences – for instance by encouraging conscious control of movement in patients with a pronounced inclination to reinvest.

To elucidate the putative role of reinvestment in motor rehabilitation after stroke, and to help therapists to reliably gauge reinvestment preferences of stroke patients, we first need a measure that allows reliable assessment of reinvestment already from the start of rehabilitation. One such measure could be the Movement-Specific Reinvestment Scale (MSRS).[181] The MSRS is a self-report measure that comprises 10 statements about moving in general, with 5 statements referring to the subscale of Movement Self-Consciousness (MS-C; e.g., 'I am concerned about what people think about me when I'm moving'), and the other 5 referring to the Conscious Motor Processing subscale (CMP; e.g., 'I try to think about my movements when I carry them out'). Both a dichotomous (disagree/agree) and 6-point Likert Scale English language version (ranging from 'strongly disagree' to 'strongly agree') have been validated for use in healthy adults, particularly in the context of sports.[180,181]

As of yet, it is unclear whether the MSRS is of sufficient psychometric quality to be suitable to measure reinvestment of rehabilitating stroke patients. A recent study[29] has reported (a Dutch translation of) the dichotomous version of the MSRS to have sufficient test-retest reliability (ICC = .85) when administered within a relatively small group (n=45) of chronic community-dwelling individuals with stroke (*M* = 2.7 years since stroke). While promising, several issues warrant further investigation before the MSRS can be applied within a clinical stroke population. First, and most importantly, Kleynen et al.[29] neither investigated the structural and construct validity of the MSRS, nor did they report on the internal consistency of its two subscales. Second, it is unclear whether test-retest values obtained within a chronic stroke population are applicable to individuals involved in clinical rehabilitation. Both motor[182] and cognitive functioning[183] often improve rapidly during the clinical rehabilitation period, possibly resulting in less 'stable' reinvestment tendencies. Finally, considerable measurement error was reported by Kleynen et al.[29] This might be due to their use of dichotomous answer possibilities, as scales with less than 5-answer options seem unfit to detect small clinically significant differences.[184]

This study aimed to address the issues outlined above, through comprehensive assessment of the validity and reliability of a 6-point Likert scale version of the MSRS for use in an inpatient stroke population (<1 year post-stroke) and healthy peers. For the purpose of this study, we used a Dutch translation of the original English MSRS[181] Structural validity of the MSRS was assessed by means of confirmatory factor analysis. Its construct validity was tested by assessing whether patients with stroke have significantly higher MSRS scores than healthy peers (as in Orrell et al.[28]). Reliability tests included test-retest reliability, internal consistency, standard error of measurement (SEM) and minimal detectable change.

2. Methods

2.1. Participants

One-hundred inpatient individuals with stroke and 100 age-matched healthy controls participated in this study. This sample size was based on the assumption that for confirmatory factor analysis a subject-to-variable ratio of 10 is sufficient.[185] Patients were recruited in the Dutch rehabilitation centres Heliomare in Wijk aan Zee and Aardenburg in Doorn. Controls were recruited in the community. Recruitment took place across three measurement periods (November 2013-January 2014, May 2014-July 2014, and September 2014-October 2014).

Patients with stroke were eligible for participation if they (1) had suffered brain injury due to stroke; (2) no longer than 12 months ago; (3) were currently receiving inpatient rehabilitative care; and (4) were able to provide informed consent and understand Dutch instructions, as assessed by their physical therapist or neuropsychologist. No in- or exclusion criteria were formulated with regard to patients' motor functioning. Inclusion criteria for the control group were as follows: (1) no neurological, musculoskeletal, or cognitive impairments; (2) similar age as the stroke group; (3) able to provide informed consent and understand Dutch instructions.

Demographic characteristics of patients were obtained from their medical files and included: age, gender, days since stroke, days spent in the inpatient rehabilitation ward, lesion type (infarction, haemorrhagic), lesion location (left cortex, right cortex, bilateral cortices, stem/cerebellar), and aphasia (yes/no). Age and sex of control participants were registered. All participants signed an informed consent. The protocol was approved by the ethical committee of the Faculty of Human Movement Sciences in Amsterdam.

2.2. Materials

The MSRS English version[181] (Appendix 4.1) was translated for the purpose of this study. This self-report scale includes 10 items. Five items relate to the construct of feeling self-consciousness about moving (Movement Self-Consciousness) whereas the other 5 items relate specifically to conscious motor control (Conscious Motor Processing). Items are scored on a 6-point Likert scale ranging from 1 (strongly disagree) to 6 (strongly agree; as in[186,187]). Sum scores therefore range between 5-30 for each subscale, and between 10-60 for the whole MSRS. The scale can usually be administered within 5 minutes.

2.3. Procedure

The MSRS was translated into Dutch following the recommendations of Guillemin, Bombardier, and Beaton.[188] First, three independent (native Dutch speaking) translators converted the MSRS-EV into a Dutch version and reached consensus on the best translation. Two independent translators (one native English speaker and one native Dutch speaker, both qualified English-Dutch translators) converted the consensus translation back to English. In the final, third round, a group of experts considered all translations made, and decided on the final version. Group members included individuals with knowledge of the concept of reinvestment, individuals who work with stroke patients, and all translators. The final Dutch language version of the MSRS can be found in Appendix 4.2.

Participants completed the newly translated MSRS on two occasions (T1 and T2), with one week in-between (on average 7.1 ± 3.1 days). We considered this test-retest period to be sufficiently short to minimize possible changes in patients' motor and cognitive function between measurements due to natural or therapeutic recovery, and sufficiently long to prevent recall bias. Patients with stroke always completed the scale following a regular physical or occupational therapy session, to ensure that test conditions were similar at T1 and T2. If necessary (e.g., for patients with problematic sight or aphasia), items and answer alternatives were read aloud by a research assistant.

2.4. Data analysis & statistics

All data were analysed with SPSS and AMOS software (version 21; IBM, Chicago, United States). Missing values were dealt with by imputing the median score on the respective item (2 items – or 0.1% of cases - in both groups). Outliers were removed from further analyses when the difference in total MSRS score between T1 and T2 exceeded the mean group difference by 3 z-scores or more *and* if additional reasons for removal were already noted when the scale was administered (e.g., suspicion of difficulty with comprehending instructions).

2.4.1. Structural validity

To investigate structural validity of the MSRS, confirmatory factor analysis was performed using structural equation modelling in AMOS. Confirmatory factor analysis tests whether the data fit the hypothesized two-factor model of the MSRS (i.e., that the scale contains the CMP and MS-C factors, as reported in healthy adults).[181] The data of T1 of all participants (both patients and controls) served as input for this analysis. The procedure entailed analysis of the variance-covariance matrix with maximum likelihood estimation†.[189] Items were constrained to load on the factors they should load on (either on the CMP or MS-C subscale; Appendix 4.1). As scores on the CMP subscale should be moderately correlated to scores on the MS-C subscale,[181] these factors were allowed to co-vary. Pairs of error terms within each factor were allowed to co-vary only if this improved fit of the model.

As recommended[190] the structure of the final model, standardized item-factor loadings, and several model fit tests were reported. Model fit tests were the chi-square statistic - both raw (X^2) and divided by its degrees of freedom (X^2/df; both should be close to zero for good fit[191]), goodness-of-fit and comparative fit indices (GFI and CFI; values > .90 indicate acceptable fit, and > .95 good fit[192]), standardized root mean squared residual (SRMR; values ≤.08 indicate good fit[191]), and the root mean square error of approximation (RMSEA; values < .05 indicate good fit, .05-.08 acceptable fit, and >.08 marginal to poor fit[193]).

Subsequently, measurement invariance of the overall final model was determined, to assess whether factor structure was similar for the patient and control group.[194] To this end, model fit was assessed when item-factor loadings were free to differ between patient and control groups (unconstrained testing), when item-factor loadings were equated across groups (so-called weak/metric invariance testing), and when both the item-factor loadings and the intercepts of the model were equated across groups (so-called strong invariance[194]). When model fit is statistically similar in all these three analyses – as indicated by non-significant X^2 values and a difference in CFI of .1 or less[195] – the factor structure is similar for patients with stroke and controls.

† This procedure was justified, as skewness and kurtosis of each item was well below the recommended[189] values (M_{skew} = .62 < 2, M_{kurt} = .25 < 7).

2.4.2. Construct validity

Construct validity was assessed by testing whether the MSRS could differentiate healthy controls from individuals with stroke.[196] Bonferroni corrected independent-samples t-tests were used to test the hypothesis that individuals with stroke had higher CMP and MS-C scores than healthy controls. Data collected at T1 served as input for this comparison. Significance level was set at $p = .05$.

2.4.3. Reliability

Reliability indices and measurement error were calculated for both groups separately. Internal consistency of the CMP and MS-C subscales (at T1) was assessed with Cronbach's alpha. Test-retest reliability for the total score, and for scores on the CMP and MS-C subscales was assessed with a 2-way, random effect, consistency, single measures ICC[197]‡. Both ICC and Cronbach's alpha values should be higher than .70 for sufficient reliability. Finally, measurement error was assessed by calculation of the standard error of measurement ($SEM = SD_{measurement1+2}\sqrt{1-ICC}$[198]) and by calculating the minimal detectable change on the group and on the individual level ($MDC_{group} = SEM \times 1.96 \times \sqrt{2}/\sqrt{n}$; $MDC_{individual} = SEM \times 1.96 \times \sqrt{2}$).[198,199]

‡ All three variables were normally distributed in the patient group, but somewhat positively skewed in the control group ($M_{skew} = 0.9$). As ICC is highly robust to slight deviations from normality[197] we chose to use the original (non-transformed) data for this analysis.

3. Results

One-hundred patients with stroke and one-hundred healthy peers were included. Of these 98 patients and 97 healthy controls were included in the validity and internal consistency analyses, whereas 97 patients and 91 healthy peers were included in the retest-reliability analysis (see Figure 4.1. for details on the inclusion process). Group characteristics are presented in Table 4.1.

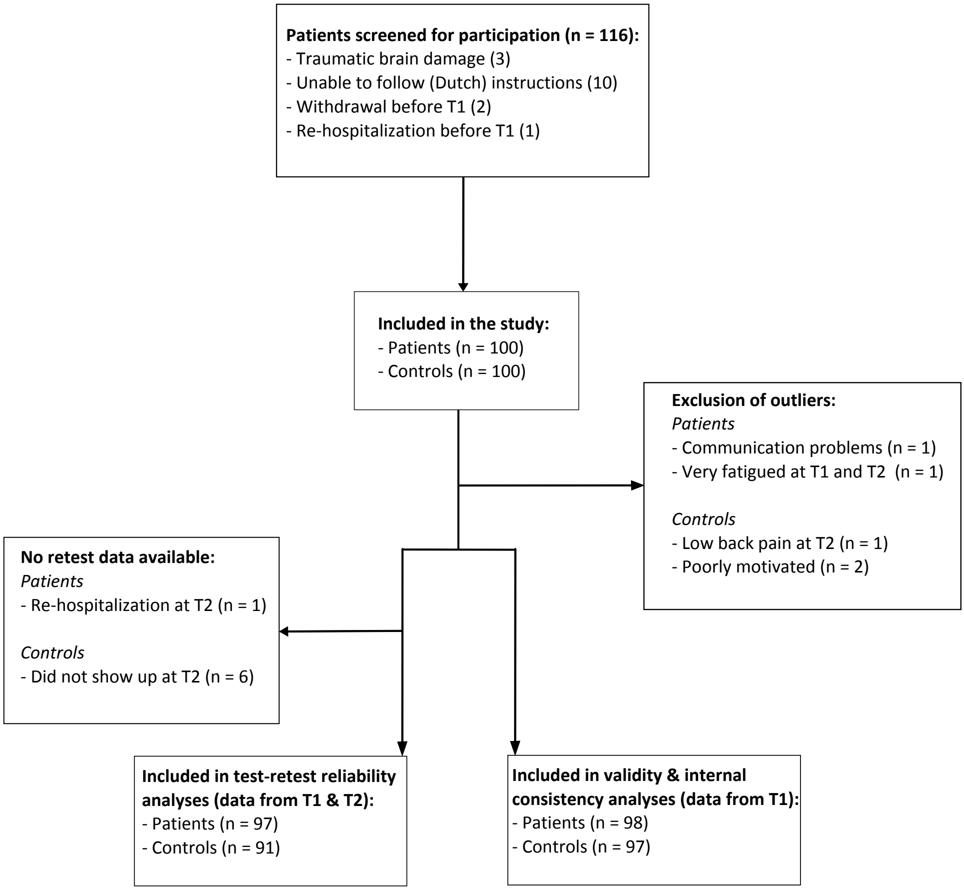


Figure 4.1. Flowchart of inclusion of stroke patients and healthy controls.

Table 4.1. Group Characteristics

Demographic variable	Stroke	Control
n	98	97
Age (SD)	57.9 (11.4)	59.7 (10.0)
Male/Female	58/40	52/45
Stroke type		N/A
Hemorrhagic	25	
Infarct	73	
Stroke location		N/A
Right	52	
Left	26	
Bilateral	5	
Stem/Cerebellar	12	
Unspecified	3	
Days since stroke* (range)	63 (11-266)	N/A
Days in rehabilitation* (range)	44 (3-259)	N/A
Aphasia (Yes/No)	13/85	N/A

NB: N/A = not applicable; *Defined at T1;

3.1. Validity

3.1.1. Structural validity

A total number of 195 (98 patients + 97 controls) participants were included in the analysis. The final overall model of the CFA is presented in Figure 4.2. Model fit was best when several pairs of error terms within the MS-C subscale were co-varied (Figure 4.2). Considerable covariance was observed between the CMP and MS-C factors (.78). Standardized item-factor loadings were all in the expected direction (i.e., positive), and of substantial magnitude (>.5). Most importantly, model fit indices were acceptable to good ($X^2(31) = 50.6$, $p = .015$; $X^2/\text{df} = 1.63$; GFI = .95; CFI = .98; SRMR = .045; RMSEA = .057, [90% CI = .026-0.085]). Subsequent tests revealed that this model demonstrated both weak ($X^2(8) = 4.6$, $p = .80$; ΔCFI = .007) and strong measurement invariance ($X^2(11) = 15.9$, $p = .14$; ΔCFI = .01). Thus, factor analysis confirmed the hypothesized two-factor structure of the MSRS, both for the patient and control group.

3.1.2. Construct validity

Summed reinvestment scores of both groups are presented in Table 4.2. The hypothesis for construct validity was supported by independent-samples t-tests. Stroke patients scored higher on the MSRS than controls, both with regard to the CMP ($t(183.8) = 13.5$, $p < .001$, $d = 1.9$, 95% CI = [8.7 12.7]), and MS-C subscale ($t(172.9) = 10.3$, $p < .001$, $d = 1.5$, 95% CI = [6.0 9.8]). Additional t-tests showed that CMP scores were higher than MS-C scores, both for patients ($t(97) = 10.6$, $p < .001$, $d = 2.2$, 95% CI = [5.1 7.4]) and controls ($t(96) = 6.5$, $p < .001$, $d = 1.3$, 95% CI = [2.4 4.5]).

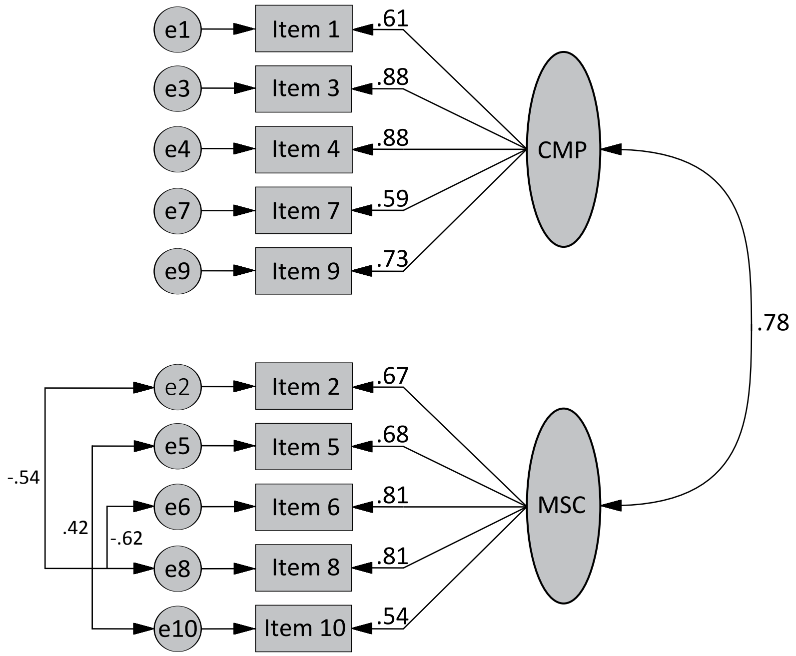


Figure 4.2. Final overall model yielded by the CFA. Shown (above the arrows) are the standardized factor loadings of each item and the amount of covariance between the factors CMP and MS-C. Allowing covariance between the error terms of three pairs of items (items 5–10, items 2–8, and items 6–8) yielded the best fitting model. Item numbers refer to the items on the questionnaire (see Appendices). NB: CMP = Conscious Motor Processing subscale; MS-C = Movement Self-Consciousness subscale; e = residual error;

3.2. Reliability

Table 4.3 lists all reliability measures. For the control group, internal consistency was satisfactory. For patients, Cronbach's alpha of the CMP-subscale was somewhat below the threshold of .70, but still of substantial magnitude§. Test-retest indices showed a similar pattern of results, with the CMP-subscale scoring slightly below cut-off in the patient group (.70). Observation of the range of scores on this subscale revealed that limited variance may partially account for this: on T1, all patients scored above 5 on the CMP subscale.

§ Additional analysis of the inter-item correlation matrix revealed that item 1 ("I remember the times when my movements have failed me") correlated poorly with items 3 (r = .16) and 9 (r = .11), and demonstrated weak item-total correlation (i.e., r < .3). However, it was decided not to remove this item, considering that confirmatory factor analysis showed item 1 to have satisfactory factor loading (.61), and since removal of this item would only slightly improve Cronbach's alpha of the CMP subscale (α = .67).

The SEM and minimal detectable change were greater for patients than for controls. Specifically, on an individual level the minimal detectable change for the total MSRS score was almost twice as large in patients (12.5) as in controls (6.9). As the total score can range between 10 and 60, it therefore seems that individual changes in MSRS score of 25% or more can be reliably detected in patients with stroke. On group level, however, the minimal detectable change for the total scale and the two subscales was adequate in both groups (i.e., ≤ 1.2).

Table 4.2. Summed reinvestment scores (± SE) for both groups at T1 and T2.

Group	MSRS-DLV score	T1	T2
Stroke			
	Total Scale	40.8 ± 1.0	38.6 ± 1.1
	CMP	23.5 ± 0.5	22.4 ± 0.5
	MS-C	17.2 ± 0.6	16.1 ± 0.7
Control			
	Total Scale	22.2 ± 1.0	19.8 ± 0.9
	CMP	12.6 ± 0.6	11.4 ± 0.6
	MS-C	9.4 ± 0.4	8.4 ± 0.4

NB: Scores are presented separately for the total scale (MSRS-DLV) and for each subscale (CMP and MS-C). Of note, differences between T1 and T2 can be somewhat distorted as 1 stroke patient and 6 healthy controls only completed the MSRS-DLV at T1. Abbreviations: NB: CMP = Conscious Motor Processing; MS-C = Movement Self-Consciousness; MSRS = Movement-Specific Reinvestment Scale;

Table 4.3. Reliability measures for both groups.

		Stroke	Control
ICC (95% CI)			
	Total Scale	0.80 (0.71-0.86)	0.92 (0.89-0.95)
	CMP	0.67 (0.54-0.76)	0.91 (0.86-0.94)
	MS-C	0.79 (0.71-0.86)	0.84 (0.77-0.89)
Internal Consistency (α)			
	CMP	0.66	0.77
	MS-C	0.74	0.69
SEM			
	Total Scale	4.5	2.5
	CMP	2.9	1.8
	MS-C	2.9	1.5
MDC (individual level)			
	Total Scale	12.5	6.9
	CMP	8.0	5.0
	MS-C	8.0	4.2
MDC (group level)			
	Total Scale	1.2	0.7
	CMP	0.8	0.5
	MS-C	0.8	0.4

NB: CMP = Conscious Motor Processing; MS-C = Movement Self-Consciousness; ICC = Intraclass Correlation Coefficient; MDC = minimal detectable change; SEM = standard error of the measurement;

4. Discussion

It has been proposed that the tendency to consciously control motor actions by ‘reinvesting’ attentional resources delays motor recovery after stroke.[28,93] As a first step to investigate this hypothesis, this study validated (a Dutch language version of) the Movement-Specific Reinvestment Scale for use in an inpatient stroke population and healthy age-matched peers. Structural validity was supported by factor analysis, which confirmed the two-factor structure obtained by earlier studies within healthy adults.[180,181] In addition, construct validity was verified, as the MSRS successfully differentiated inpatient stroke patients from healthy peers. Furthermore, test-retest reliability and internal consistency were adequate in both groups. Taken together, the MSRS seems a valid and reliable instrument to measure reinvestment tendencies of inpatient patients with stroke and healthy age-matched controls.

This study was the first to assess the validity of the MSRS to measure reinvestment tendencies after stroke. Similar to earlier studies,[180,181] when administered to stroke patients, the MSRS encompasses two latent factors, with 5 items relating to one's tendency to engage in conscious motor control (CMP subscale) and 5 measuring the degree to which one feels self-conscious about one's style of moving (MS-C subscale). Tests of construct validity showed that patients with stroke scored higher than controls on both these subscales, reproducing findings with the English MSRS within a chronic stroke population.[28] Further support for the validity of the MSRS's two-factor structure stems from the finding that patients with stroke scored higher on the CMP subscale than on the MS-C subscale, replicating earlier findings with chronic stroke patients.[28,29] and patients with Parkinson's disease.[200] It is doubtful that both subscales are of equal clinical relevance, though. Theoretically, one would expect the CMP subscale to be of more relevance than the MS-C subscale, as the former directly concerns one's motor control preferences, whereas the latter merely gauges whether one feels awkward about one's style of moving. Indeed, there is some evidence to support this hypothesis. For instance, higher CMP scores have been found to be uniquely associated with more severe motor impairments in people with stroke,[28] with an increased risk of falling in healthy elderly,[180] with duration of Parkinson's disease,[200] and with more self-reported knee pain in healthy adults.[187] Since no such associations have been reported for individuals' MS-C scores, researchers and rehabilitation therapists may be especially interested in patients' scores on the CMP subscale. Further exploration of the unique associations between MS-C and CMP scores and motor behaviour after stroke is needed.

For the patient group, test-retest reliability indices of the total scale and MS-C subscale were comparable to those reported by Kleynen et al.[29] It seems that in this study the CMP subscale is somewhat less reliable, however. This might be due to the fact that this inpatient stroke population generally is in a less 'stable' situation than the chronic stroke population studied by Kleynen and colleagues. In addition, as noted earlier, low variance in scores on the CMP subscale may have attenuated test-retest reliability. Finally, the use of a 6-point Likert scale (instead of a dichotomous one) may have compromised reliability, as it may have been somewhat more difficult to complete. For the stroke group, internal consistency values of both subscales were similar to those of English and French versions of the MSRS when tested in healthy adults.[181,201] With regard to the control group, both retest reliability and internal consistency were satisfactory to good, replicating findings obtained within young healthy adults.[181]

Next to validity and reliability, the utility of the MSRS depends on its measurement error. In this study, although the minimal detectable change of the total scale (12.5 points or 25% of total scale range) was slightly better than the measurement error reported by Kleynen et al.[29] (3 points or 27% of total scale range), it was still relatively large. However, the minimal detectable change was considerably better when assessed on a group level (1.2 points for the total scale, and 0.8 for each subscale). This suggests that the MSRS is suitable to compare reinvestment tendencies across different groups, but is less suitable for tracking individual changes in reinvestment after stroke. In other words, the MSRS may be especially useful for scientific purposes, but needs further refinement for clinical applications. It is unclear how measurement error for the control group compares to earlier work, as this is the first study to report on the minimal detectable change in reinvestment score within healthy (elderly) individuals. Nonetheless, the minimal detectable change for this group seemed adequate both on a group and individual level.

A strength of the present study is that the study population was representative for the general stroke population that is admitted for clinical rehabilitation in a rehabilitation center in the Netherlands. All inpatient people with stroke were screened for participation (n=116). About 86% of these participated, among whom a considerable number of aphasic patients (13%). Of note, a limitation is that we assessed the validity and reliability of the MSRS within a Dutch stroke population. Nonetheless, our results likely also hold true for other stroke populations, as the scale was translated in accordance with cross-cultural validation guidelines [20]. A more poignant limitation of the MSRS is that it seems less useful for patients with severe aphasia and/or substantial cognitive impairments, as they made up the majority of patients who were excluded from participation. Also, a practical limitation of the MSRS is that questions and answer possibilities need to be read aloud for many patients (e.g., 33% in our study), mostly due to problems with vision (e.g. neglect) or aphasia. Relatedly, a limitation of the present study is that we did not specifically assess cognitive and motor abilities of patients. As our in- and exclusion criteria were quite lenient, it is likely that there was large heterogeneity in terms of cognitive and motor functioning in the patient population. Even so, the MSRS was found to be reliable.

Finally, although technically beyond the scope of this study, our data allowed an interesting side-speculation. That is, two observations from our data may nuance the idea that patients' increased tendency to reinvest is the result of the predominance of explicit motor learning strategies[43,178] within current rehabilitation practice.[28] First, a considerable number of patients (± 25%) were tested within the first two weeks since the start of rehabilitation. Second, no significant association was observed between the time spent in rehabilitation at T1 and reinvestment score ($r < .3$, $p > .1$), suggesting that reinvestment does not change substantially throughout rehabilitation. Based on this, we speculate that reinvestment is not necessarily a strategy patients gradually acquire in the course of rehabilitation. Instead, patients with stroke may already have become highly prone to reinvest even before rehabilitation commences, and remain so throughout the rehabilitation period. Whether this impedes patients' motor recovery (as argued by Orrell et al.[28]) remains an open question. In this regard, the results of Stillman and co-workers are worth mentioning.[202] They reported that healthy (young and old) people who are more predisposed to be mindful (or: " to stay attentive and receptive to events and experiences taking place in the present and thus disengage from habitual actions and thought tendencies", p. 141) have a reduced implicit motor learning ability. Considering the apparent similarities between the concepts of reinvestment (or more specifically: conscious motor processing) and mindfulness, one may speculate that many stroke patients with a strong disposition to reinvest are less able to learn motor skills implicitly. This would be also in line with reports that people with higher reinvestment tendencies are more likely to engage in *explicit* motor learning.[203] Future research should explore this hypothesis, by further mapping the relation between motor recovery and dispositional reinvestment post-stroke.

5. Conclusion

We conclude that the MSRS is a valid and reliable tool to measure reinvestment after stroke. The clinical usefulness of this tool for individual patients remains to be determined though. In order to establish this, future studies need to assess (1) whether reinvestment indeed impairs motor functioning post-stroke, and (2) whether the MSRS is accurate enough to measure clinically meaningful changes in reinvestment over time in individual patients.

6. Acknowledgements

We would like to thank Christa de Jonge, Charlotte Postma, Nynke Bos, and Mette van Kruijsbergen for their contributions to the data collection, Jacinta Kal and Steven Barker for their aid in the translation process, and dr. Wouter Weeda for his valuable statistical advice.

Appendix 4.1. English Movement-Specific Reinvestment Scale[181]

DIRECTIONS: Below are a number of statements about your movements in general. Circle the answer that best describes how you feel for each question.

English Movement-Specific Reinvestment Scale

1. I remember the times when my movements have failed me

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

2. If I see my reflection in a shop window, I will examine my movements

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

3. I reflect about my movement a lot

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

4. I try to think about my movements when I carry them out

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

5. I am self-conscious about the way I look when I am moving

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

6. I sometimes have the feeling that I am watching myself move

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

7. I am aware of the way my body works when I am carrying out a movement

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

8. I am concerned about my style of moving

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

9. I try to figure out why my actions failed

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

10. I am concerned about what people think about me when I am moving

1	2	3	4	5	6
strongly disagree	moderately disagree	weakly disagree	weakly agree	moderately agree	strongly agree

NB: Items 2, 5, 6, 8, and 10 refer to the subscale Movement Self-Consciousness (MS-C). Items, 1, 3, 4, 7, and 9 refer to the subscale Conscious Motor Processing (CMP);

Appendix 4.2: Movement-Specific Reinvestment Scale – Dutch language version (MSRS-DLV)

Naam: **Datum:**

INSTRUCTIE: Hieronder staan een aantal uitspraken over uw bewegen in het algemeen. Lees deze goed door en omcirkel het antwoord dat het beste bij u past.

1. Ik kan me herinneren wanneer het me niet lukte mijn beweging uit te voeren

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

2. Als ik mijn spiegelbeeld zie, bekijk ik mijn bewegingen

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

3. Ik denk veel na over mijn bewegingen

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

4. Ik probeer na te denken over mijn bewegingen als ik ze uitvoer

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

5. Ik voel me ongemakkelijk over hoe ik eruit zie tijdens het bewegen

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

6. Ik heb het gevoel dat ik mezelf bekijk tijdens het bewegen

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

7. Ik ben me bewust van de manier waarop mijn lichaam werkt als ik een beweging uitvoer

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

8. Ik maak me zorgen over mijn manier van bewegen

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

9. Ik probeer uit te zoeken waarom mijn bewegingen mislukken

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

10. Ik maak me zorgen over wat anderen van mij denken als ik beweeg

1	2	3	4	5	6
helemaal mee oneens	redelijk mee oneens	een beetje mee oneens	een beetje mee eens	redelijk mee eens	helemaal mee eens

Chapter 5

Over-focused? The relation between patients' inclination for conscious control and single- and dual-task motor performance after stroke

Rosalie Denneman
Elmar Kal
Han Houdijk
John van der Kamp

Gait & Posture. 2018;62:206-213

Abstract

Background: Many stroke patients are inclined to consciously control their movements. This is thought to negatively affect patients' motor performance, as it disrupts movement automaticity. However, it has also been argued that conscious control may sometimes benefit motor performance, depending on the task or patients´ motor or cognitive capacity. We aimed to assess whether stroke patients' inclination for conscious control is associated with motor performance, and explore whether the putative association differs as a function of task (single- vs dual) or patients´ motor and cognitive capacity.

Methods: Univariate and multivariate linear regression analysis were used to assess associations between patients' disposition to conscious control (i.e., Conscious Motor Processing subscale of Movement-Specific Reinvestment Scale; MSRS-CMP) and single-task (Timed-up-and-go test; TuG) and motor dual-task costs (TuG while tone counting; motor DTC%). We determined whether these associations were influenced by patients' walking speed (i.e., 10-meter-walk test) and cognitive capacity (i.e., working memory, attention, executive function).

Results: Seventy-eight clinical stroke patients (<6 months post-stroke) participated. Patients' conscious control inclination was not associated with single-task TuG performance. However, patients with a strong inclination for conscious control showed higher motor DTC%. These associations were irrespective of patients' motor and cognitive abilities.

Conclusions: Patients' disposition for conscious control was not associated with single task motor performance, but was associated with higher motor dual task costs, regardless of patients' motor or cognitive abilities. Therapists should be aware that patients' conscious control inclination can influence their dual-task performance while moving. Longitudinal studies are required to test whether reducing patients' disposition for conscious control would improve dual-tasking post-stroke.

1. Introduction

A motor task like walking is often assumed to be a relatively automated task that requires minimal cognitive involvement.[22,204] However, walking may invoke enhanced degrees of conscious control in special circumstances, such as under fatigue or stress, or in special groups, such as elderly with fear of falling or rehabilitating patients.[23,28,41,93,205] For example, following a stroke individuals typically become strongly inclined to consciously guide their movements, and consider this necessary for ensuring successful locomotion and preventing falls.[28] Physiotherapists tend to encourage such conscious control, by providing patients with explicit movement-related knowledge and rules to execute their movements,[42] cf.[206]. However, it remains uncertain to what degree conscious control is actually functional, and whether this would depend on patients' inclination for conscious control.

Theoretically, conscious control is regarded a dysfunctional strategy – at least in healthy adults. Maxwell and Masters[93] argued that individuals with strong disposition for conscious control "de-chunk" motor skills to control each chunk separately. This would result in less automated, more jerky movements, and consequently, suboptimal performance. Indeed, such "trait" conscious motor control has been found to have negative effects on motor performance. In healthy adults and elderly, people with stronger inclinations for conscious control are more likely to experience performance degradation or even a total performance break-down when they feel anxious about their performance, or when they have to perform multiple tasks simultaneously.[23,41,93,204,207] Similarly, instructions that promote state conscious control also result in suboptimal motor performance and learning.[86,208]

Based on these observations in healthy adults, it has been proposed that stroke patients' generally strong conscious control inclinations may impede their motor recovery.[28,29,134] Yet, evidence is scarce: only Orrell and Masters[28] related patients' conscious control inclination to their motor recovery. Results showed that patients with a relatively strong inclination for conscious control (i.e., as measured by higher scores on the Conscious Motor Processing subscale of the Movement-Specific Reinvestment Scale (MSRS-CMP)) experienced larger impairments in activities of daily life.[28] However, studies that directly manipulated patients' state conscious control through instructions provide ambiguous evidence. Two studies found that instructions that trigger conscious motor control (i.e., internal focus) had a negative impact on patients' motor performance,[209,210] while three studies did not find any effect.[211–213] Also, one study reported trends toward better dual-task performance when stroke patients were given instructions that aimed to trigger conscious control, rather than "external" focus instructions that aimed to minimize conscious control (by directing attention to the task goal).[212]

For clinical practice, the question thus remains: what are therapists to do? Should they attempt to reinforce or reduce patients' conscious motor control inclination?[212] We suspect that a proper answer requires taking into account 1) the strength of patients' inclination for conscious control, 2) the task constraints, and 3) patients' cognitive and motor capacities. With regard to the first, there are indications that promoting conscious control (for instance with internal focus instructions) may be more beneficial to motor performance for people with a stronger inclination for conscious motor control, while the reverse may be true for performers with a weak inclination.[212,214,215] Regarding task constraints, conscious control of movement is thought to place significant demands on cognitive resources such as working memory and attention.[57,93,96] Hence, a strong conscious control inclination may be especially detrimental to performance in cognitively demanding conditions, such as when performing two tasks concurrently. Similarly, with regard to patients' cognitive capacities, a strong conscious control inclination may be detrimental to performance of cognitively impaired patients, but may be relatively beneficial for motor performance in patients with better cognitive capacity. Finally, motor capacity may also be an important factor; it has been proposed that some degree of movement automaticity has to be established before it can be disrupted by conscious control.[93] Accordingly, a strong conscious control inclination may disrupt motor performance of patients with mild or no motor impairments, but benefit performance of patients with severe motor impairments. Indeed, preliminary evidence in healthy adults[216,217] and stroke patients[212] points in this direction.

Our primary study aim was to further explore the relation between stroke patients' inclination for conscious control and motor performance. To this end, we assessed whether clinical stroke patients' inclination for conscious control (i.e., as indicated by the MSRS- CMP[181,212]) is associated with performance on a clinical mobility test (Timed-up-and-Go; TuG[218,219]). In addition, we intended to explore whether the purported relations differ as a function of task constraints and patients' motor and cognitive capabilities. To this end, patients performed the TuG both in single- and dual-task conditions. We hypothesized, first, that a strong inclination for conscious control is associated with worse single- and dual-task motor performance. Second, we hypothesized this negative relationship to be more pronounced in dual-task conditions and for patients with better walking ability and worse cognitive capacity.

2. Methods

2.1. Participants and setting

We included patients with stroke who received inpatient rehabilitative care in Heliomare Rehabilitation Centre in Wijk aan Zee, the Netherlands between 27 January and 7 March 2017. Participants were recruited for a larger RCT, either in the pilot phase (n=11) or in the proper experimental trial (n=67).[220] We refer to this paper for details on patients' inclusion.[220] Inclusion criteria were: First-ever or recurrent stroke <6 months ago, FAC>2, able to stand independently >1 minute, able to understand instructions and cooperate with neuropsychological assessment, no other central nervous system or orthopaedic impairments, and no uncorrected visual/hearing impairment. Figure 5.1 shows the study flow.

Power analysis with G*power showed inclusion of at least 65 patients to be necessary to find a moderately strong association (f=0.20) between the inclination for conscious control and motor performance (linear multiple regression, alpha-level of 0.05, beta of 0.80, and four independent variables).

2.2. Ethics statement

All participants provided written informed consent. The study protocol was approved by the medical-ethical committee of the VU Medical Centre in Amsterdam (VUMC protocol ID: 2015.354).

2.3. Data collection

The following tests and outcomes were used:

Conscious motor control inclination: Movement-Specific Reinvestment Scale, which consists of a Conscious Motor Processing Subscale (MSRS-CMP) and a Movement Self Consciousness subscale (MSRS-MSC)**.** This questionnaire is meant to assess a person's inclination to reinvest and has been validated for use in clinical stroke patients.[134] As our research question concerns the former, only results for the MSRS-CMP are reported. The data for the MSRS-MSC can be found in Appendix 5.3. MSRS-CMP comprises five statements about conscious motor processing in movements in daily life (e.g., 'I reflect about my movement a lot').[181] Statements are scored on a 6-point Likert scale ranging from 1 (strongly disagree) to 6 (strongly agree), with total scores ranging between 5-30 points. Higher scores reflect stronger inclination for conscious control.[221]

Motor task: Patients performed the Timed-up-and-Go (TuG), a mobility test that is frequently used in clinical practice.[218,219] For this test patients stand up from a chair, walk three meters, turn around and sit down again, all at comfortable speed.[219] Motor performance is defined as the time needed to complete the test (in seconds). Participants were allowed to use a walking aid if required.[219] The TuG is sensitive to interference from cognitive tasks, such as talking, and has good reliability and satisfactory construct validity.[218,222,223]

Cognitive dual-task: In dual-task conditions, participants had to concurrently perform the TuG with a tone counting-task.[56] For this test high and low tones were randomly presented every 1500 milliseconds. Participants were required to respond as accurately and quickly as possible by saying 'yes' when the tone was high-pitched and instructed to count the number of high-pitched tones.[56] On completion of each trial, participants were asked to report the total number of high-pitched tones. They received feedback regarding counting accuracy.[56] In single-task conditions, participants simply sat on the chair and performed the tone counting task for 30 seconds. The tone counting task is challenging enough to induce dual-task interference in stroke patients, and is suitable for most patients with expressive aphasia.[212]

Walking speed: As measure of motor capacity, we assessed patients' comfortable walking speed using the 10-meter walk test. For this test, patients walk a 10-meter straight path at three consecutive times.[224] The mean time needed to complete the trials is recorded (in seconds). This test has no ceiling effect and excellent reliability and construct validity.[225,226]

Cognitive capacity. Participants' education level was recorded as measure for general cognitive ability.[227] Trained neuropsychologists administered specific tests of working memory (total number of correct sequences on Digit Symbol Substitution Test DSST),[228] executive function (interference score on Color Trails Test; CTT),[229] and sustained attention (concentration performance score on D2-test).[230] All tests have acceptable psychometric properties,[228–230] and are suitable for most aphasic patients.[212]

Finally, the Nottingham Sensory Assessment (NSA) was administered to describe patients' gnostic and vital sensibility and proprioception.[231]

2.4. Procedure

Measurements were performed on two occasions. On the first occasion, participants completed the neuropsychological assessment (i.e., DSST, CTT, and D2-test). The remaining tests (Appendix 5.1) were administered by the researcher or trained research assistants in a second session. First, patients' were familiarized with the TuG and tone counting task, to make sure that they understood the tasks and were able to discriminate between the high and low tones. This session started with the 10-MWT, followed by the single-task tone counting assessment, the single-task TuG (TuG-ST), and the dual-task TuG (TuG-DT). For the TuG-DT trials, participants were not specifically instructed to prioritize either task. For reliable assessment and to minimize bias due to fatigue, each test was performed twice, with the order reversed during the second series.[224] The MSRS and the NSA were administered on completion of the second session. Other patient characteristics[157,232–235] were obtained from patients' medical files (see Table 5.1).

2.5. Instrumentation

For the tone counting task, high (1000 Hertz) and low pitch (400 Hertz) stimuli were presented for 300 milliseconds with customized LabVIEW software (National Instruments; Austin; Texas) via high quality speakers, which were positioned at two meters from the side of the walkway. Verbal responses were recorded with a directional microphone using LabVIEW, and sampled at 1000 Hz.

2.6. Data analysis

The total MSRS-CMP score is the sum of the five statements of this subscale, and ranges between 5-30. Single-task TuG was defined as the mean time needed to perform the two TuG-ST trials. Single-task tone counting performance (i.e., reaction accuracy (%), counting accuracy (%), and reaction time in ms) was analysed using customized Matlab software.[212] To correct for a possible speed-accuracy trade off, a composite score was calculated per trial (Equation 5.1).[236] An average composite score was calculated for the single- and dual-task conditions separately.

$$Composite\ Score\ = \frac{average\ counting + reaction\ time\ accuracy(\%)}{median\ verbal\ reaction\ time\ (ms)} \quad \textbf{[5.1]}$$

To assess dual-task performance, we calculated the dual-task costs (DTC%; Equation5.2).[14,212] Positive DTC% reflects deterioration of performance in dual-task relative to single-task conditions.[14] DTC% was calculated for both the TuG (i.e., Motor DTC%; note that for the TUG -100% was used as multiplier to ensure that positive values indicated a decrease in performance during dual-tasking).) and tone counting task (i.e., Cognitive DTC%).

$$DTC\ (\%)\ = 100\%\ x\ \frac{(single-task\ performance)-(dual-task\ performance)}{single-task\ performance} \quad \textbf{[5.2]}$$

2.7. Statistics

First, we assessed the association between the inclination for conscious control (MSRS-CMP score) and single-task TuG performance with univariate linear regression. Second, we used similar regression analysis to assess the association between the MSRS- CMP score and motor DTC%. Cognitive DTCs% were added as covariate, to correct for possible task prioritization differences between participants.¶ In addition, Holm-Bonferroni[237] t-tests assessed whether significant dual-task interference occurred (i.e., if DTC% significantly differed from zero). Alpha was set at 0.05.

¶ We primarily focused on the relation between patients' inclination for conscious control and motor dual-task performance. This because conscious should more directly impact motor control (and hence motor dual-task costs). Any effects on cognitive dual-task costs could only arise indirectly, through increasing attentional costs of movement. To make sure that cognitive dual-task costs did not confound our results we did include them as a covariate. For comprehensiveness, we include a subsidiary analysis in which we assessed the relation between patients' conscious motor control inclination and cognitive dual-task costs in Appendix 5.2.

Next, we explored for both models whether walking speed (10-MWT) and cognitive capacity (i.e., DSST, CTT, D2-test) influenced the associations between MSRS-CMP and TuG. This was done by evaluating the interaction of each variable with MSRS-CMP. Each variable was tested in separately. For these modification analyses, alpha was Bonferroni-corrected to 0.0125 (0.05/4).

For all regression analyses, the assumptions of homoscedasticity (inspection of plot of standardized residuals and predicted values), error-independence (Durbin-Watson>corresponding boundaries), lack of multicollinearity (VIFs<1.6, tolerances>0.6), and normal distribution of errors were verified (i.e., Kolmogorov-Smirnov-test).** Two participants were excluded from the analyses in which we explored how 10-MWT performance influenced the relation between MSRS-CMP and TuG-ST. For both participants it was found that Cook's distances>1, suggesting that they disproportionately influenced group results.

3. Results

3.1. Patient inclusion and characteristics

Figure 5.1 shows the study flow. In total, 238 stroke patients were screened for participation, 78 of whom were eventually included in the study (M_{age}=59.1±10.8 years; 49 men, $M_{days\ since\ stroke}$=31.9±19.7). Table 5.1 details all patient characteristics, including the outcomes of the TuG assessments, 10-Meter Walk Test, and cognitive tests.

3.2. Relation between stroke patients' conscious control inclination and single-task TuG

Figure 5.2 shows patients' TuG performance in single-task conditions. Univariate linear regression analysis showed no association between patients' MSRS-CMP score and single-task TuG performance (p=0.710; Table 5.2A). Patients' total MSRS-CMP score did not interact with walking speed (10-MWT; p=0.944), working memory (DSST; p=1.00), sustained attention (D2; p=1.00), or executive function (CTT; p=0.240). Thus, patients' inclination for conscious control was not related to their single-task motor performance, regardless of their comfortable walking speed or cognitive capacities.

** Kolmogorov-Smirnov was significant for two multivariate regression analyses with TuG-ST as dependent variable. These concerned the analyses in which we explored the interaction between MSRS-CMP and (1) 10-meter walk test, and (2) CTT-scores (both: KS>0.120, p<0.05). However, plots did not show substantial deviations from normality, and log-transformation of the dependent variable did not significantly improve the KS values. Therefore, our main analyses concerned the untransformed TuG-ST. For these two analyses, we do report the results of the regression analyses with log-transformed TuG-ST in Table 5.2.

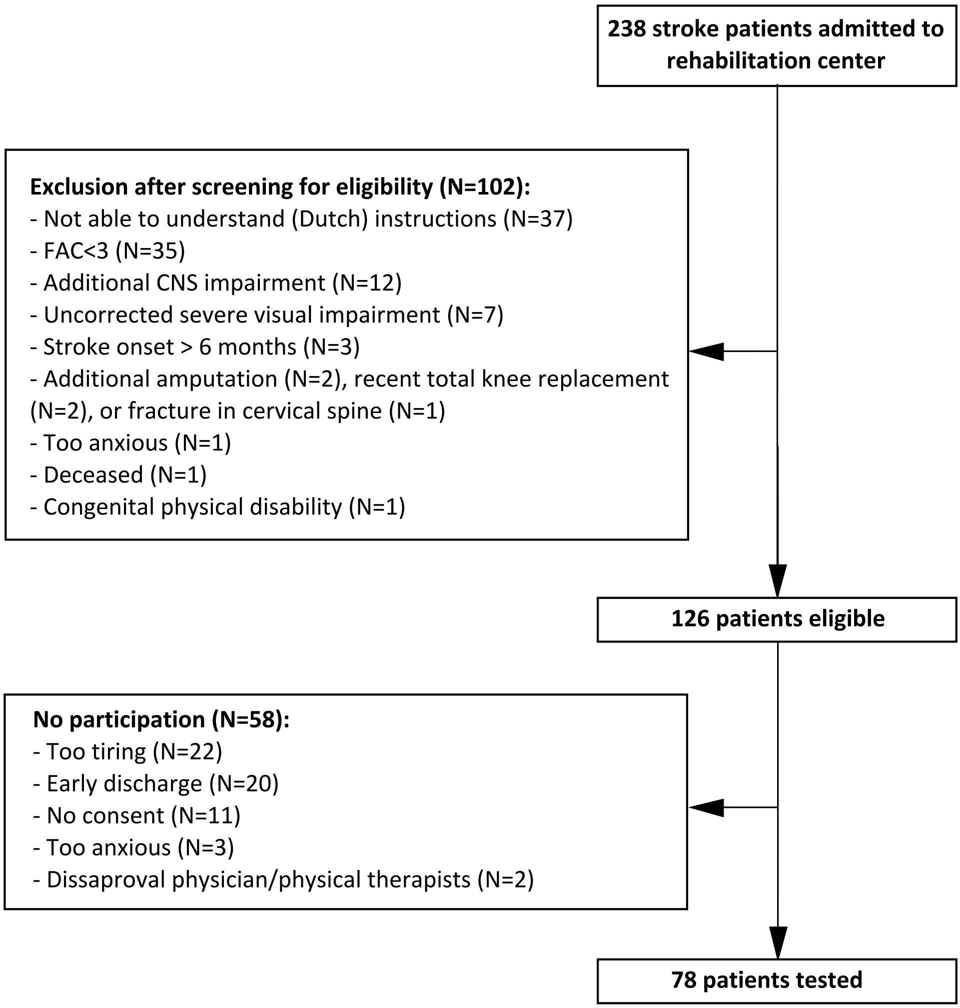


Figure 5.1 Flowchart of inclusion. NB: CNS = Central nervous system; FAC = Functional Ambulation Categories.

3.3. Relation between stroke patients' conscious control inclination and motor dual-task costs

Figure 5.2 shows the average TuG performance in dual-task conditions, while Figure 5.3 shows the average composite scores on the tone counting task. Both motor TuG DTCs (i.e., 8.28±10.80) and cognitive tone-counting DTCs (i.e., 4.49±19.20) significantly differed from zero ($t=6.727$, $p<0.001$, $d=0.767$; and $t=2.039$, $p=0.045$, $d=0.234$ respectively). Thus, patients walked significantly slower and performed significantly worse on the tone-counting task in dual-task compared to single-task conditions.

Univariate linear regression analysis showed a positive association between MSRS- CMP and motor DTCs ($p=0.033$; Table 5.2B). Patients' MSRS-CMP score did not interact with walking speed (10 MWT; $p=0.904$), working memory (DSST; $p=1.00$), sustained attention (D2; $p=1.00$), and executive function (CTT; $p=0.468$). Combined, patients with a stronger inclination for conscious control (i.e. higher MSRS-CMP scores) showed worse dual-task performance, regardless of their comfortable walking speed or cognition.

Table 5.1. Patient characteristics (N=78).

General characteristics	Value
Age in years (mean±SD)	59.1±10.8
Sex (male/female)	49/29
Stroke characteristics	
Days since stroke (mean±SD)	31.9±19.7
Days since admission (mean±SD)	16.1±15.4
Stroke aetiology (haemorrhagic/ischemic)	18/60
Side of affected hemisphere (left/right/NA)	38/35/5
Stroke subtype (n)	
TACS/PACS/LACS/POCS/PACS+POCS	4/38/20/15/1
Recurrent stroke, yes/no	6/72
Aphasia, yes/no	18/60
Neglect, yes/no	19/59
NSA (0-80; mean±SD)	72.4±9.6
CCI (mean±SD)	0.7±1.2
Motor functioning	
Walking device (walker/cane/none)	21/16/41
Walking orthosis (yes[a]/no)	17/61
BBS (0-56; mean±SD)	47.3±9.6
FAC (3/4/5)	22/31/25
10-MWT (s, mean ±SD)	15.1±8.8
TuG-ST (s; mean±SD)	17.9±11.2
TuG-DT (s; mean±SD)	19.3±12.0
Cognitive functioning	
Education level (1-7; median±25th; 75th percentile)	5 (4; 6)
DSST[b] (mean±SD)	45.5±18.1
D2-test[b] (mean±SD)	118.2±45.4
CTT[b] (mean±SD)	1.0±0.5
Conscious control inclination	
MSRS-CMP (5-30; mean±SD)	21.5±5.9
General functioning	
USER-mobility (0-35; mean±SD)	24.4±7.1
USER-cognitive (0-50; mean±SD)	44.4±4.7

NB: 10-MWT = 10-meter walk test[224]; AFO =Ankle Foot Orthosis; BBS =Berg Balance Scale[232]; CCI = Charlson Comorbidity Index[234]; CTT=Color Trails Test[229]; DSS = Digit Symbol Substitution Test[228]; FAC = Functional Ambulation Categories[225]; LACS = Lacunar stroke; MSRS-CMP = Conscious Motor Processing subscale of Movement-Specific Reinvestment Scale[181]; NSA = Nottingham Sensory Assessment[231]; PACS = Partial Anterior Circulation Stroke; POCS = Posterior Circulation Stroke; TACS = Total Anterior Circulation Stroke; USER: Utrecht Scale for Evaluation of Rehabilitation[233];

[a] Fifteen patients used an Ankle-Foot-orthosis, one patient used a toe-off orthosis and one patient used functional electrical stimulation of the m. peroneus;

[b] Several participants did not complete the DSST (n=6), D2-test (n=6) and/or CTT (n=9), due to no patient consent (n=2), no therapeutic consent (n=1), early discharge (n=1) or difficulties in comprehending one or more of these neuropsychological tests;

Table 5.2A. Summary of linear regression analyses of single-task motor performance

Association with MSRS-CMP	B	p	95% CI of B	R^2	R^2-change
Inclination for conscious control ***(MSRS-CMP)***	0.081	0.710	-0.352, 0.515	0.002	
Effect Modification[a]	**B**	**p**	**98.75% CI of B**[b]	**R^2**	**R^2- change**[b]
Motor capacity (***10-MWT***)[c,d]	1.670	0.000*	0.886, 2.454	0.810	0.807*
MSRS-CMP x 10-MWT	-0.017	0.944	-0.054, 0.019		
Working memory (***DSST***)	0.115	1.00	-0.739, 0.969	0.031	0.030
MSRS-CMP x DSST	-0.010	1.00	-0.050, 0.029		
Sustained attention (***D2***)	-0.026	1.00	-0.292, 0.240	0.008	0.008
MSRS-CMP x D2	0.000	1.00	-0.012, 0.012		
Executive function (***CTT***)[e]	21.365	0.264	-8.043, 50.774	0.054	0.053
MSRS-CMP x CTT	-0.979	0.240	-2.291, 0.334		

Table 5.2B. Summary of linear regression analyses of motor dual-task costs[f]

Association with MSRS-CMP	B	p	95% CI of B	R^2	R^2-change
Inclination for conscious control ***(MSRS-CMP)***	0.461	0.033*	0.038, 0.883	0.067	
Cognitive dual-task costs	0.049	0.446	-0.078, 0.176		
Effect Modification[a]	**B**	**p**	**98.75% CI of B**	**R^2**	**R^2-change**
Motor capacity (***10-MWT***)	-0.716	0.540	-1.931, 0.498	0.103	0.035
MSRS-CMP x 10-MWT	0.026	0.904	-0.029, 0.081		
Working memory (***DSST***)	-0.089	1.00	-0.939, 0.760	0.062	0.004
MSRS-CMP x DSST	0.002	1.00	-0.037, 0.042		
Sustained attention (***D2***)	-0.084	1.00	-0.338, 0.169	0.080	0.011
MSRS-CMP x D2	0.004	1.00	-0.008, 0.015		
Executive function (***CTT***)	-12.765	0.968	-40.540, 15.010	0.138	0.071
MSRS-CMP x CTT	0.765	0.468	-0.472, 2.002		

NB: *B* = unstandardized coefficients; MSRS-CMP = Movement-Specific Reinvestment Scale; CMP = subscale Conscious Motor Processing; 10-MWT = 10-meter walk test; DSST = Digit Symbol Substitution Test; CTT = Color Trails Test;
*: $p<0.05$, *italics:* $p<0.1$;

[a] For each variable, a separate model was run;
[b] The effect modification analyses were corrected using Bonferroni, such that alpha was 0.0125, and the confidence intervals were 98.75%;
[c] Two participants had to be excluded due to Cook's >1;
[d] Results did not substantially change when log-transformed TuG-ST scores were used: 10-MWT x MSRS interaction, p=1.00;
[e] Results were slightly less distinct when log-transformed TuG-ST scores were used: CTT x MSRS-CMP interaction, p=0.296;
[f] For the analyses of motor and cognitive dual-task costs one person was removed – this because of consistently outlying scores on the tone counting task (mean Z-score = 2.6) and earlier doubts as to whether this person understood the task correctly. Sensitivity analyses showed that including this patient in the analyses would not substantially alter results;

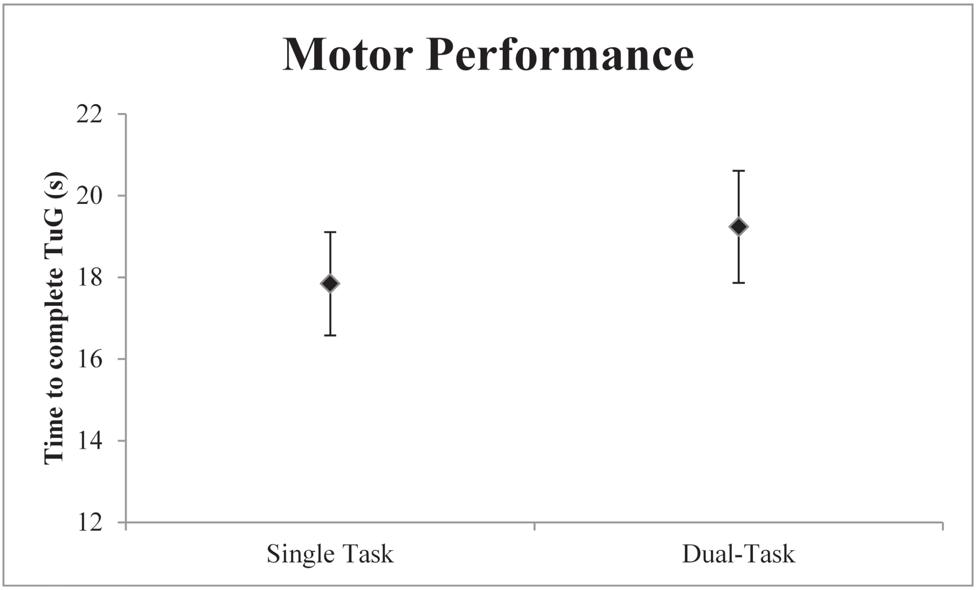


Figure 5.2. Average single- and dual-task motor performance. Time to complete the Timed- up-and-Go Test in seconds ± standard error. NB: TuG, Timed-up-and-Go-test; s, seconds;

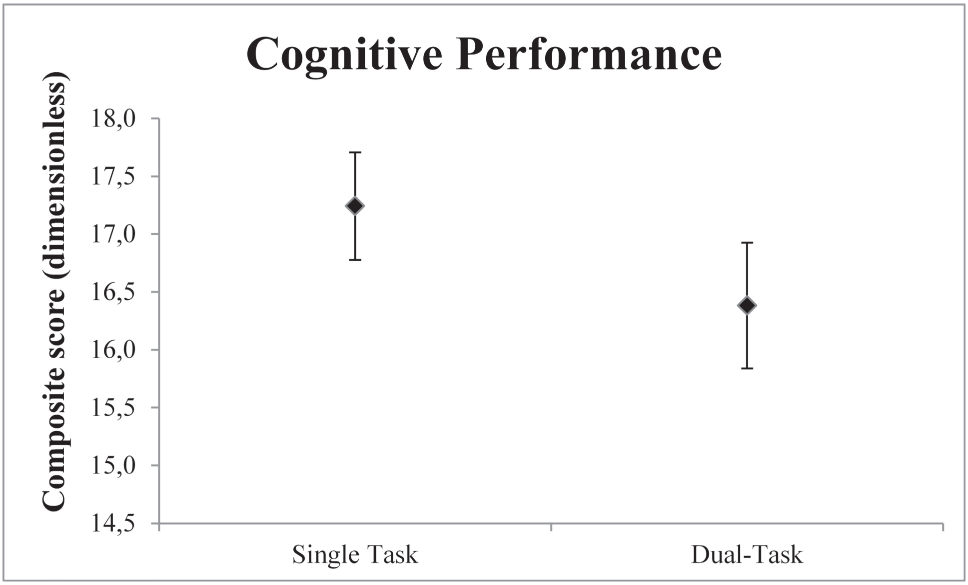


Figure 5.3. Average single- and dual-task tone-counting performance. Tone-counting performance expressed as a composite score (± standard error) whereby accuracy (%) was divided by reaction time in milliseconds. Higher composite score indicate better performance. NB: Average reaction time (ms) in single task conditions was 571±12 and in dual-task conditions was 603±16. Average reaction accuracy (± Standard Error) in single-task conditions was 93.1%±0.8 and in dual-task conditions was 90.8±1.1;

4. Discussion

This study examined the relation between the inclination for conscious motor control and motor performance in clinical stroke patients. Also, we explored the possible modulatory role of task constraints (single- versus dual-task conditions) and patients' motor and cognitive capacities.

4.1. Main findings

As expected, stroke patients in this study scored high on the MSRS-CMP subscale (21.5±5.9) – that is, comparable to scores reported in earlier studies in stroke patients,[28,134,212] but significantly higher than in healthy older adults.[180,207,238] Thus, patients in our sample were on average strongly inclined to consciously control their movements.

We hypothesized that stronger conscious control inclinations would be associated with worse motor performance, and more so in cognitively demanding dual-task conditions. This hypothesis was partly confirmed: Patients with stronger conscious control inclination showed similar single-task TuG performance compared to patients with weaker inclinations, but they did demonstrate significantly greater slowing down of TuG performance when required to perform a dual-task. Hence, if we assume that patients with a stronger conscious control inclination (or trait) are inherently more likely to adopt a conscious control strategy across motor tasks and conditions, then it appears that this is an appropriate strategy to perform movements in relatively easy, single-task conditions. However, when required to dedicate a large chunk of their cognitive capacity to dual-task performance, these patients do no longer have sufficient cognitive resources to consciously control movements, resulting in a break-down of motor performance. Our findings may partly explain the results of Orrell et al.[28] who found that chronic stroke patients with higher MSRS-CMP scores experience greater impairments in daily life. Perhaps, these observations are due to a dual-tasking deficit, considering that most activities of daily life require patients to divide attention between two or more tasks (e.g. walking when talking, attending to the traffic lights while crossing the street).

An alternative (but not necessarily mutually exclusive) explanation for our findings may be that patients with stronger dispositions for conscious control become especially triggered to do so in dual-task conditions, but much less so in the single-task condition. Masters and Maxwell[6] predict that people with a stronger conscious control inclination are more easily triggered to do so when they are anxious about their performance, but not necessarily in low-pressure environments (when compared with people with weaker inclinations, that is). For many stroke patients, having to perform dual-tasks may certainly be perceived as threatening. Patients may worry about their ability to successfully divide their attention, as well as about the possible consequences of failing to do so (i.e., falling). If so, it could certainly be that this especially triggered patients with stronger conscious control inclinations to rely on conscious control while dual-tasking - which ironically seemed to impair their dual-task performance. It is difficult to say which of these explanations holds true, considering that we did not measure patients' state anxiety or include an additional check in the form of verbal protocols to determine where patients focused on during the TuG tasks. In fact, it may well be that both mechanisms are at work. Future research is needed to examine these propositions.

Patients' comfortable walking speed and cognitive characteristics did not influence the association between their conscious control inclination and single-task TuG performance or dual-task costs. Hence, there is no evidence for our hypotheses that stronger conscious control inclinations would be especially detrimental to motor performance of patients with better walking ability or poor cognition. With regard to the cognitive tests, the absence of results may be an artefact of the chosen tasks. All three tasks (DSST, D2, and CTT) were deliberately selected because they could also be used for assessment of patients with expressive aphasia. By definition these tests thus do not (or minimally) require verbal processing. However, conscious motor control has been suggested to rely on such verbal- analytical processing.[93,204] Future studies may specifically investigate whether patients' scores on tests of verbal cognitive processing determine whether conscious control will benefit or harm their motor performance.

4.2. Clinical implications

We found that patients with a strong inclination for conscious control showed greater decrements in motor performance in dual-task conditions compared to patients with less pronounced conscious control inclinations. This observation is of importance for clinical practice, as increased dual-task interference may impede daily functioning and increase fall risk.[17] On the one hand, this seems to suggest that conscious control might negatively impact dual-tasking ability, and that therapists may therefore attempt to minimize their patients' inclination for conscious control (i.e., in those patients who score high on the CMP subscale). On the other hand, reducing gait speed during dual-tasking may also be a strategy that patients adopt to ensure safety of walking. We must emphasize that we cannot determine causality based on the current cross-sectional design, and this requires further longitudinal research. In any event, our results do show that a stroke patient's conscious control inclination may be an important factor for successful dual-tasking.

If therapists want to minimize patients' inclination for conscious control, one potential method would be implicit motor learning.[68] With implicit learning, patients become only minimally aware of the specifics of what is learned. As a result, they will be less likely to acquire verbal rules and knowledge that they can use to control their movements (see Kleynen et al.[47] for an overview and examples of specific implicit motor learning interventions). We encourage therapists in daily rehabilitation practice to experiment with implicit motor learning interventions for patients with strong conscious control inclinations. Still, when doing so, therapists need to be aware that applied implicit motor learning research in stroke rehabilitation is still in its infancy.[96] Also, recent studies suggest that some patients – such as those with more severe motor impairments – may benefit more from strategies that promote explicit, conscious control of movement rather than from implicit strategies (see[212]). Future research is needed to delineate (subgroups of) patients that could benefit from strategies that promote (explicit) conscious motor control and learning, and those that benefit more from implicit strategies.

4.3. Strengths and limitations

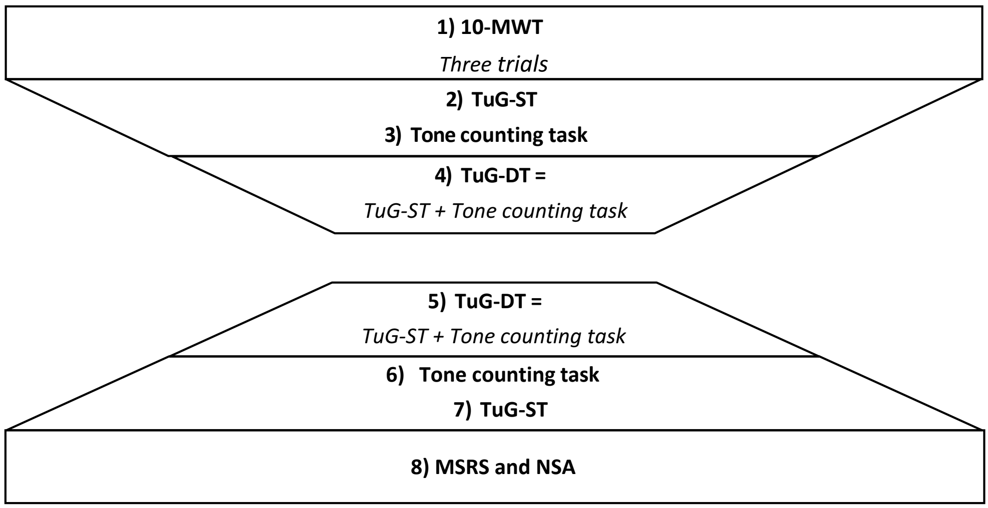
A primary limitation of this study was its cross-sectional design, which prohibits inferences about causality. Second, we performed multiple separate effect modification analyses per variable. This likely increased the possibility of chance findings. On the other hand, these analyses had been planned beforehand and alpha was corrected with Bonferroni. Another potential limitation of the current study is that we did not investigate the role of patients' scores on the Movement Self-Consciousness (MS-C) subscale of the MSRS. Factor analyses show that CMP and MS-C subscales measure different concepts.[134,181] While the CMP scale is thought to specifically measure conscious motor control, the MS-C scale primarily relates to self-awareness. Recent studies also suggest that the MS-C score reflects the extent to which a person monitors (but not controls) movement execution.[239,240] In fact, Van Ginneken et al.[240] found that MS-C score (but not CMP score) positively correlated with a person's mindfulness score. This suggests that the MS-C subscale measures the degree to which someone observes his/her movements, *without attempting to consciously control them*. Considering the uncertainty as to the specific construct measured by the MS-C, we decided to focus on the CMP subscale. We did include results of linear regression analyses with the MS-C scores in Appendix 5.3. Overall, MS-C scores were not associated with TuG-ST or motor dual-task costs. A final methodological limitation of our study was that the duration of the single-task trials on the tone counting task was always set at 30 seconds, whereas many patients walked faster in the dual-task trials. Thus, duration of trials did not always match. We are confident that this did not affect the outcome of our dual-task analysis, though. We repeated the regression analysis of motor dual-task costs, but now added dual-task TuG performance as covariate as well to correct for a potential effect of trial duration (next to the independent variables CMP and cognitive dual-task cost). Results were unchanged: CMP was still significantly associated with dual-task costs, and both B and p-values only showed minor changes (B=0.439, p=0.043, 95%CI [0.013, 0.865]).

A strength of this study is the large sample size. Also, the stroke group was fairly heterogeneous in terms of motor, cognitive, and stroke characteristics, and therefore representative for the sub-acute stroke population with walking ability. Further, the motor task used (TuG) is a clinically relevant mobility task that is often used in clinical practice. Combined, this makes our results directly relevant to clinical practice.

5. Conclusion

Motor performance was less robust to dual-task interference for stroke patients with stronger inclination for conscious control compared to patients with weaker inclinations, regardless of their motor or cognitive abilities. Longitudinal studies are needed to investigate whether reducing patients' strong conscious control inclination would improve their dual- tasking ability.

Appendix 5.1. Test procedures



NB: 10-MWT = 10-meter-walk test; TuG-ST = Timed up-and-Go test in single-task condition; TuG-DT = Timed up-and-Go test in dual-task condition; MSRS =Movement-Specific Reinvestment Scale; NSA = Nottingham Sensory Assessment;

Appendix 5.2. Relation between MSRS-CMP and cognitive DTCs

Univariate linear regression analysis showed no association between MSRS-CMP and cognitive DTCs (*p*=0.776; Table A.5.2). Patients' MSRS-CMP score did not interact with walking speed (10 MWT; *p*=1.00), working memory (DSST; *p*=1.00), sustained attention (D2; *p*=1.00), and executive function (CTT; *p*=0.908). Combined, there was no association between patients' inclination for conscious motor control and cognitive dual-task costs, regardless of their comfortable walking speed or cognition.

Table A.5.2. Summary of linear regression analyses of cognitive dual-task costs[c]

Association with MSRS-CMP	**B**	**p**	**95% CI of B**	**R^2**	**R^2-change**
Inclination for conscious control ***(MSRS-CMP)***	-0.114	0.776	-0.909, 0.681	0.008	
Motor dual-task costs	0.163	0.446	-0.261, 0.587		
Effect Modification[a]	**B**	**p**	**98.75% CI of *B*[b]**	**R^2**	**R^2-change[b]**
Motor capacity (***10-MWT***)	0.978	1.000	-1.184, 3.141	0.103	0.095
MSRS-CMP x 10-MWT	-0.015	1.000	-0.113, 0.083		
Working memory (***DSST***)	-0.125	1.000	-1.699, 1.418	0.032	0.026
MSRS-CMP x DSST	-0.003	1.000	-0.074, 0.069		
Sustained attention (***D2***)	0.004	1.000	-0.456, 0.464	0.025	0.025
MSRS-CMP x D2	-0.003	1.000	-0.024, 0.018		
Executive function (***CTT***)	24.917	0.836	-25.559, 75.393	0.026	0.025
MSRS-CMP x CTT	-1.077	0.908	-3.347, 1.193		

NB: *B* = unstandardized coefficients; MSRS-CMP = Movement-Specific Reinvestment Scale; CMP = subscale Conscious Motor Processing; 10-MWT = 10-meter walk test; DSST = Digit Symbol Substitution Test; CTT = Color Trails Test;
**: p*<0.05, *italics: p*<0.1;
[a] For each variable, a separate model was run;
[b] The effect modification analyses were corrected using Bonferroni, such that alpha was 0.0125, and the confidence intervals were 98.75%;
[c] For the analyses of motor and cognitive dual-task costs one person was removed – this because of consistently outlying scores on the tone counting task (mean Z-score = 2.6) and earlier doubts as to whether this person understood the task correctly. Sensitivity analyses showed that including this patient in the analyses would not substantially alter results;

Appendix 5.3. Relation between stroke patients' movement self-consciousness inclination (MSRS-MS-C), singe-task motor performance, motor dual-task costs, and cognitive dual-task costs

Relation between patients' movement self-consciousness inclination and single-task TuG

Patients' average score on the MSRS-MS-C was 14.6±5.7. Univariate linear regression analysis showed no association between patients' MSRS-MS-C score and single-task TuG performance (p=0.680; Table A.5.3A). Patients' total MS-C score did not interact with walking speed (10-MWT), working memory (DSST), or sustained attention (D2; all p's=1.00). Yet, MS-C scores did interact with executive function (CTT; p=0.024). To explore this latter finding in more detail, the patient group was subdivided in a low executive function and high executive function group by means of median split. Separate linear regression analyses were run for both subgroups to identify the association between MS-C scores and TuG-ST performance. Results showed that higher MSRS-MS-C scores were associated with slower performance on the TuG-ST (B=0.273) for people with high executive function (Interference score < 0.90). In contrast, higher MSRS-MS-C scores were associated with faster TuG-ST times (B=-0.646) in people with low executive function (Interference score > 0.90). There is no straightforward explanation for these findings. One recent interpretation of MS-C is that it reflects the inclination to monitor (i.e., paying attention) movements (Malhotra et al. 2015). One might speculate that people who have high self-consciousness will be more likely to monitor their movements, but especially so when they have high executive functions as well. This enhanced monitoring may then lead to slower single-task performance. Future work is necessary to test this ad-hoc hypothesis, and further disentangle the unique contributions of MS-C and CMP to motor control and learning.

Relation between patients' movement self-consciousness inclination and motor dual-task costs

Univariate linear regression analysis showed no association between MSRS-MS-C and motor DTCs (p=0.100; Table A.5.3B). Patients' MSRS-MS-C score did not interact with walking speed (10 MWT), working memory (DSST), sustained attention (D2), or executive function (CTT; all p's≥0.408). Combined, there was no relationship between patients' MSRS- MS-C scores and motor dual-task performance.

Relation between patients' movement self-consciousness inclination and cognitive dual-task costs

Univariate linear regression analysis showed no association between MSRS-MS-C and cognitive DTCs (p=0.199; Table A.5.3C). Patients' MSRS-MS-C score did not interact with walking speed (10 MWT), working memory (DSST), sustained attention (D2), or executive function (CTT; all *p*'s≥0.872). Combined, there was no relationship between patients' MSRS-MS-C scores and cognitive dual-task performance.

Table A.5.3A. Summary of results of linear regression analyses for single-task motor performance

Association with MSRS-MS-C	**B**	**p**	**95% CI of B**	**R^2**	**R^2- change**
Inclination for movement self- consciousness ***(MSRS-MS-C)***	-0.093	0.680	-0.543, 0.357	0.002	
Effect Modification[a]	**B**	**p**	**98.75% CI of *B***	**R^2**	**R^2- change**
Motor capacity (***10-MWT***)[c,d]	1.532	0.000*	1.023, 2.040	0.823	0.823
MSRS-MS-C x 10-MWT	-0.023	0.344	-0.058, 0.011		
Working memory (***DSST***)	-0.003	1.000	-0.518, 0.513	0.021	0.019
MSRS-MS-C x DSST	-0.005	1.000	-0.038, 0.027		
Sustained attention (***D2***)	-0.028	1.000	-0.216, 0.160	0.008	0.005
MSRS-MS-C x D2	0.001	1.000	-0.011, 0.013		
Executive function (***CTT***)[d]	20.835	0.036*	1.021, 40.649	0.115	0.109
MSRS-MS-C x CTT	-1.414	0.024*	-2.701, -0.128		

Table A.5.3B. Summary of results of linear regression analyses for motor dual-task costs[e]

Association with MSRS-MS-C	**B**	**p**	**95% CI of *B***	**R^2**	**R^2- change**
Inclination for movement self-consciousness ***(MSRS-MS-C)***	0.370	0.100	-0.073, 0.812	0.043	
Cognitive dual-task costs	0.062	0.347	-0.068, 0.192		
Effect Modification	**B**	**p**	**98.75% CI of *B***	**R^2**	**R^2- change**
Motor capacity (***10-MWT***)	-0.681	0.240	-1.592, 0.231	0.091	0.048
MSRS-MS-C x 10-MWT	0.042	0.408	-0.023, 0.107		
Working memory (***DSST***)	0.081	1.000	-0.425, 0.587	0.049	0.004
MSRS-MS-C x DSST	-0.006	1.000	-0.038, 0.026		
Sustained attention (***D2***)	-0.013	1.000	-0.190, 0.163	0.067	0.002
MSRS-MS-C x D2	0.001	1.000	-0.010, 0.012		
Executive function (***CTT***)	5.309	1.000	-14,535, 25,153	0.094	0.027
MSRS-MS-C x CTT	-0.132	1.000	-1.417, 1.152		

Table A.5.3C. Summary of results of linear regression analyses for cognitive dual-task costs

Association with MSRS-MS-C	**B**	**p**	**95% CI of *B***	**R^2**	**R^2- change**
Inclination for movement self-consciousness ***(MSRS-MS-C)***	-0.517	0.199	-1.311, 0.278	0.029	
Motor dual-task costs	0.196	0.347	-0.217, 0.609		
Effect Modification	**B**	**p**	**98.75% CI of *B***	**R^2**	**R^2- change**
Motor capacity (***10-MWT***)	0.360	1.000	-1.264, 1.984	0.119	0.090
MSRS-MS-C x 10-MWT	0.022	1.000	-0.094, 0.138		
Working memory (***DSST***)	-0.168	1.000	-1.075, 0.738	0.044	0.017
MSRS-MS-C x DSST	0.002	1.000	-0.056, 0.059		

Sustained attention (***D2***)	-0.025	1.000	-0.343, 0.292	0.023	0.018
MSRS-MS-C x D2	-0.002	1.000	-0.022, 0.018		
Executive function (***CTT***)	17.701	0.780	-17.062, 52.465	0.034	0.027
MSRS-MS-C x CTT	-1.086	0.872	-3,331, 1.160		

NB: *B* = unstandardized coefficients; MSRS-MS-C = Movement-Specific Reinvestment Scale; CMP = subscale Movement Self-Consciousness; 10-MWT = 10-meter walk test; DSST = Digit Symbol Substitution Test; CTT = Color Trails Test;

*: $p<0.05$, *italics:* $p<0.1$;

[a] For each variable, a separate model was run;

[b] The effect modification analyses were corrected using Bonferroni, such that alpha was 0.0125, and the confidence intervals were 98.75%;

[c] One participant had to be excluded due to Cook's >1;

[d] Results did not substantially change when log-transformed TuG-ST scores were used: 10-MWT x MSRS-MS-C interaction, p=0.14, CTT x MSRS-MS-C interaction, p=0.036;

[e] For the analyses of motor and cognitive dual-task costs one person was removed – this because of consistently outlying scores on the tone counting task (mean Z-score = 2.6) and earlier doubts as to whether this person understood the task correctly. Sensitivity analyses showed that including this patient in the analyses would not substantially alter results;

Chapter 6

How physical therapists instruct patients with stroke: An observational study on attentional focus during gait rehabilitation after stroke

Elmar Kal
Henrieke van den Brink
Han Houdijk
John van der Kamp
Paulien Goossens
Coen van Bennekom
Erik Scherder

Disability and Rehabilitation. 2018;40(10):1154-1165

Abstract

Background: People without neurological impairments show superior motor learning when they focus on movement effects (external focus) rather than on movement execution itself (internal focus). Despite its potential for neurorehabilitation, it remains unclear to what extent external focus strategies are currently incorporated in rehabilitation post-stroke. Therefore, we observed how physical therapists use attentional focus when treating gait of rehabilitating patients with stroke.

Methods: Twenty physical therapist-patient couples from 6 rehabilitation centers participated. Per couple, one regular gait-training session was video-recorded. Therapists' statements were classified using a standardized scoring method to determine the relative proportion of internally and externally focused instructions/feedback. Also, we explored associations between therapists' use of external/internal focus strategies and patients' focus preference, length of stay, mobility, and cognition.

Results: Therapists' instructions were generally more external while feedback was more internal. Therapists used relatively more externally focused statements for patients with a longer length of stay (*B*=-.239, p=.013) and for patients who had a stronger internal focus preference (*B*=-.930, p=.035).

Conclusions: Physical therapists used more external focus instructions but more internally focused feedback. Also, they seem to adapt their attentional focus use to patients' focus preference and rehabilitation phase. Future research may determine how these factors influence the effectiveness of different attentional foci for motor learning post-stroke.

1. Introduction

A significant challenge for physical therapists working in the field of stroke rehabilitation is to effectively communicate the desired movement execution to their patients. Considering that many patients with stroke exhibit reduced information processing capacity[27] - and particularly language impairments[241] - therapists need to use instructions that are sufficiently detailed to help the patient perform the motor skill appropriately, but that at the same time do not overly burden the patient's cognitive resources. One promising way to achieve this seems to use instructions that trigger an "external" focus of attention during moving: a focus on the intended effects of the movement.[57] Many studies in people without neurological impairments have shown that such external focus instructions result in superior motor learning compared to "internal" focus instructions – i.e., instructions that trigger the learner to focus on movement execution itself.[57] For example, elderly are better able to stabilize a balance board when they practiced this task with an external focus ('keep the balance board horizontal') as opposed to an internal focus ('keep your feet horizontal').[208] Significantly, these findings seem due to an external focus being less cognitively demanding than an internal focus – hence resulting in more automatic, implicit motor control.[56,86]

Notwithstanding its potential, the benefit of external focus instructions for motor learning after stroke has not been fully confirmed. The few available studies have solely focused on immediate performance effects, and with mixed results. That is, two studies found an external focus to immediately improve reaching and sitting balance of people with stroke,[209,210] while two others found no overall differences between external and internal focus instructions for reaching[211] and leg-stepping performance.[212] Notably, the latter study even found a trend for superior dual-tasking with an internal focus.[212] Also, none of these studies actually investigated the long-term effects of *learning* with different focus instructions.

While limited, the above findings do suggest that an external focus may not *always* be superior to an internal focus for *all* patients with stroke. This begs the question which factors then determine which attentional focus strategy works best for which patient (see also Collins, Carson, & Toner[242]). One approach to get more insight into this issue is to evaluate current clinical practice, and to assess how physical therapists themselves (be it deliberately or implicitly) use different attentional focus strategies during rehabilitation post-stroke. This will inform us how often internal and external focus strategies are already used within rehabilitation post-stroke, and also whether there are specific patient factors that influence therapists' use of either of these strategies – hence providing future experimental studies on this topic with more specific leads on factors that might modify the effect of attentional focus on motor learning after stroke.

Two earlier, relatively small, studies suggest that therapists predominantly rely on internally referenced instructions and feedback (>67%) during therapy aimed at arm and gait function.[42,43] Yet, it is unclear whether these findings are representative for rehabilitation practice as a whole, given that these studies concerned a small number of therapists and were confined to the UK. Moreover, these studies did not investigate whether therapists' use of external and internal focus strategies is related to specific patient characteristics.

Therefore, we conducted an observational study among twenty therapist-patient couples from rehabilitation centres across the Netherlands. The main aim was to assess how often physical therapists use internal and external focus instructions and feedback when (re-)training gait with patients with stroke admitted for inpatient rehabilitative care. Further, we assessed whether the relative frequency with which therapists used external or internal focus strategies was associated with patients' preferred focus, rehabilitation phase, and cognitive abilities. These factors were specifically chosen based on early experimental work. For instance, studies in non-neurologically impaired adults[215] and in persons with chronic stroke[212] suggest that motor performance is enhanced when the instructed focus matches the performer's preferred focus. Further, an internal focus has been implied to be more effective in early learning stages, when motor skill is less developed, while an external focus may be more effective later in learning.[212] Finally, due to its lower cognitive demands,[57,86] an external focus may be more suitable for patients with cognitive impairments.

Based on earlier experimental work[42,43] we hypothesised that therapists would provide more internal focus than external focus instructions and feedback. In addition, we also expected that therapists would make relatively more use of internal focus cues for patients (1) with a more established internal focus preference; (2) in early rehabilitation phases – i.e., with less motor skill and shorter length of stay in rehabilitation; and (3) better cognition.

2. Methods

2.1. Participants

Physical therapists were recruited from six specialized rehabilitation centres in The Netherlands: Heliomare Rehabilitation in Wijk aan Zee, Military Rehabilitation Center in Doorn, Rijnlands Rehabilitation Center in Leiden, Sophia Rehabilitation in The Hague, Revant Rehabilitation in Breda/Goes, and Reade in Amsterdam. We aimed to include at least 2 therapists per centre and 20 therapists in total, to optimize generalizability of findings and cancel out local practice effects. Inclusion started in November 2014 and ended in September 2015.

Therapists were eligible for participation if they had at least 6 months of professional experience within stroke rehabilitation and had completed post-graduate neurorehabilitation education. Each therapist conveniently selected one patient with stroke whom he/she provided clinical (inpatient) rehabilitation therapy to improve gait (i.e., ranging from standing balance to walking stairs). Therapists were told not to select patients with receptive aphasia, but patients with expressive aphasia were eligible for participation. Therapists and patients were told the study aimed to examine (non-)verbal communication during post-stroke rehabilitation. The aim was deliberately left vague, to minimize the possibility that participants adjusted their behaviour in line with the study's aim. Full debriefing took place afterwards. Therapists and patients provided informed consent. The ethical committee of the VU University Amsterdam approved the study protocol.

2.2. Assessment of therapist and patient characteristics

Demographic information was obtained both for therapists (age, gender, years of professional experience with patients with stroke) and patients (age, gender, education level,[243] stroke characteristics, time since admission to rehabilitation centre). In addition, patients' motor abilities were scored with the Functional Ambulation Categories (FAC[244]) and Rivermead Mobility Index (RMI[245]), two recommended tests of functional mobility.[246] General cognitive functioning was assessed with the Montreal Cognitive Assessment (MoCA[247]). Patients' focus preference was assessed using a self-report instrument, the Movement-Specific Reinvestment Scale (MSRS[29,134]). Higher scores on the MSRS indicate that a patient is more strongly inclined to consciously monitor (Movement Self-Consciousness subscale; MS-C) and control (Conscious Motor Processing subscale; CMP) movements in daily life[134,181] and hence, suggest a stronger preference for an internal focus.[212]

Finally, and always after observation of the therapy session, therapists also completed a custom-made questionnaire to determine whether they (1) were familiar with the concept of internal and external attentional focus; (2) generally preferred either of these two in daily practice; and (3) made deliberate choices for either attentional focus strategy in daily practice (see Appendix 6.1). With regard to part (2) of the questionnaire, therapists were provided with five pairs of internal and external formulated statements that concerned 5 different aspects of gait. For each pair, they had to choose which option they *generally* preferred to use in daily practice. For example, for influencing "step width", therapists could choose between "try to walk with your feet in front of each other" (internal; 0 points) and "try to walk between the lines" (external; 1 point). In case a therapist had no clear preference, 0.5 point was scored. Scores could range from 0 (all internal) to 2.5 (no clear preference) to 5 (all external). The questionnaire was piloted with two physical therapists beforehand.

2.3. Procedure

First, the patient completed the MSRS and MoCA with the experimenter in a separate and quiet room. This also ensured that patients were familiarized with the experimenter and setting, and hence more at ease during the recording of the subsequent therapy session. The therapist was not present at this stage, and hence blind to the outcome of these tests.

Subsequently, for each therapist-patient couple, a regular one-to-one therapy session was recorded that focused on gait-related exercises (e.g., comprising exercises ranging from sit-to-stand transfers and standing balance to walking stairs). For this purpose, a digital camera was covertly positioned outside the participants' immediate line of sight, and therapists also wore a voice-recorder. The experimenter was present throughout the session, but did not interfere with the therapy in any way.

Afterwards, when the patient had left the room, the therapist rated the patient's score on the RMI, FAC, and MoCA (by judging patients' performance on each MoCA-item; see the published paper for this "MoCA-proxy" score form). This latter assessment thus provided us with information regarding therapists' perception of patients' cognition. Finally, therapists completed the questionnaire to determine their own preferred focus.

2.4. Data analysis

All statements were transcribed verbatim. The content of these statements was analysed with a scoring system similar to the one used by Johnson et al.[42] In short, statements were either labelled as instruction (i.e., description of how an action is to be performed), feedback (i.e., information pertaining to a previously executed movement, intended to improve future motor performance), or "other" (i.e., general talk, for instance about activities during the weekend). Instructional and feedback statements were further categorized as "internal", "external", "mixed", or "unfocused".

Reliability of scoring was ascertained as follows. First, two raters were instructed on the initial definitions of the scoring system. Subsequently, both raters independently scored ten randomly selected, 2-minute therapy fragments, blinded to each other's results. As sufficient agreement (Kappa = .60) could not be reached initially (Kappa = .49), differences between raters were discussed and definitions refined accordingly. Sufficient interrater agreement (Kappa = .64) was reached in a next round of testing, in which the raters independently scored five other randomly selected 2-minute therapy fragments. Having established its reliability, two raters each assessed half of the videos. Table 6.1 lists the final scoring method, including all scoring codes and accompanying definitions and examples.

The following variables were reported for each therapy session:

- General therapy characteristics: therapy session duration, total number of statements, and the number of statements per minute;
- Nature of statements: the proportion of instructions, feedback, and "other" statements, expressed as a percentage of the total number of statements;
- Attentional focus content of instructions: the proportion of internal, external, mixed, and unfocused instructions, expressed as a percentage of the total number of instructions;
- Attentional focus content of feedback: the proportion of internal, external, mixed, and unfocused feedback, expressed as a percentage of the total number of feedback statements;

Finally, we used linear regression analyses to explore whether therapists' relative reliance on external or internal focus strategies was influenced by patients' internal focus preference, motor skill, time spent in rehabilitation, and cognition. To determine the degree to which each therapist made more use of external or of internal focus strategies we used the following formula:

$$Relative\ Focus\ Score\ = 100\%\ x\ \frac{all\ instructions\ \&\ feedback\ with\ internal\ focus}{all\ instructions\ \&\ feedback\ with\ internal\ or\ external\ focus} \quad \mathbf{[6.1]}$$

Thus, a score of 0% means that a therapist exclusively provided external focus statements, a score of 50% means that a therapist equally often used internal and external focus statements, whereas a therapist with a 100% score exclusively provided internal focus statements. Note that we combined instructions and feedback for this analysis.

For all analyses, alpha level was set at 0.05. We then used separate univariate linear regression analyses to explore the association between therapists' relative focus scores on the one hand, and patients' internal focus preference (MSRS-CMP & MSRS-MS-C), mobility (RMI), length of stay (i.e., the number of days since the admission to the rehabilitation center at the moment of the measurement), and cognition (MoCA & MoCA-proxy) on the other hand. Multivariate linear regression analysis was planned on those independent variables that showed a (near-)significant association ($p<0.1$), to check whether these variables were uniquely associated with the outcome. The assumptions for regression analysis were verified, in that there was no multicollinearity (variance inflation factors < 1.7, tolerances > 0.6[248,249]), and no homoscedasticity (as revealed by plotting the standardized residuals against the predicted values), and that errors were independent (Durbin-Watson = 1.951 > 1.270[250]), and normally distributed (i.e., Kolmogorov-Smirnov test on residuals = 0.100, $p > 0.200$).

Table 6.1. Scoring system to classify nature (instructions/feedback/other) and attentional focus content of therapists' verbal statements.

Category	Scoring code	Definition	Example
INSTRUCTION	**I-in** - *internal focus - verbal*	Instruction to focus attention on movement execution (and body) itself	"Press your heels against your toes while walking"
	I-ex - *external focus - verbal*	Instruction to focus attention on movement goal/movement effects	'Walk the line"
	I-ex-a - *external focus, auditory*	Instruction to focus attention on auditory cues relevant to performance	"Synchronize your steps with the beat"
	I-ex-v - *external focus, visual*	Instruction to focus attention on visual cues relevant to performance	"Step toward the target that lights up"
	I-mix - *mixed focus*	Instruction that conveys both externally and internally referenced information	"Press your heel against the toes while walking the line"
	I-un - *unfocused*	Instruction that does not trigger a specific focus	"Go!"
	I-dem - *demonstration*	Demonstration of desired movement by therapist	[Therapist demonstrates walking the line]
	I-think - *'think about'*	Instruction that prompts reflection	"Think what you should do next"
FEEDBACK	**F-in** - *internal focus - verbal*	Feedback triggering a focus on movement execution (and body) itself	"Your heel did not touch your toes"
	F-ex - *external focus - verbal*	Feedback triggering a focus on movement goal/movement effects	"You stepped next to the line there"
	F-ex-a - *external focus, auditory*	Auditory cues, aimed to support/ guide motor performance	"Hop, step, hop, step, hop, step"
	F-ex-v - *external focus, visual*	Visual cues aimed to support/guide motor performance	Stepping on projected stepping stones
	F-mix - *mixed focus*	Feedback that conveys both externally and internally referenced information	"You walked the line perfectly, your heel pressing against your toes"
	F-un - *unfocused*	Feedback that does not trigger a specific focus	"This is difficult, isn't it?"
	F-dem - *demonstration*	Demonstration of previous movement by therapist	[Demonstration of patient stepping next to the line]
	F-quan - *quantified feedback*	Quantitative information about previous motor performance	"Walking here took you 20 seconds"
	F-facil - *manual facilitation*	Any tactile or manual facilitation during moving	[Therapist supports patient standing up]
	F-motiv - *motivational feedback*	Feedback aimed to motivate/ stimulate	"Well done"
OTHER	**O** - *general talk*	General talk about weather, last weekend's football, etcetera	"How are you feeling today?"

NB: Note that in some cases two codes could be assigned to one statement/action of the therapist. For example, when the demonstration of walking over a line is accompanied by the instruction to "walk the line" this is scored as "I-ex-dem" (external instruction with demonstration). The scoring system was modified from Johnson et al.[42];

3. Results

3.1. Participants

In total, 24 therapists were approached for participation. One therapist declined, whereas three other therapists did not currently had a patient under treatment for gait retraining. Also, one patient was approached but did not want to be filmed. Thus, twenty physical therapists and twenty patients with stroke participated (Figure 6.1). Therapist and patient characteristics are listed in Table 6.2.

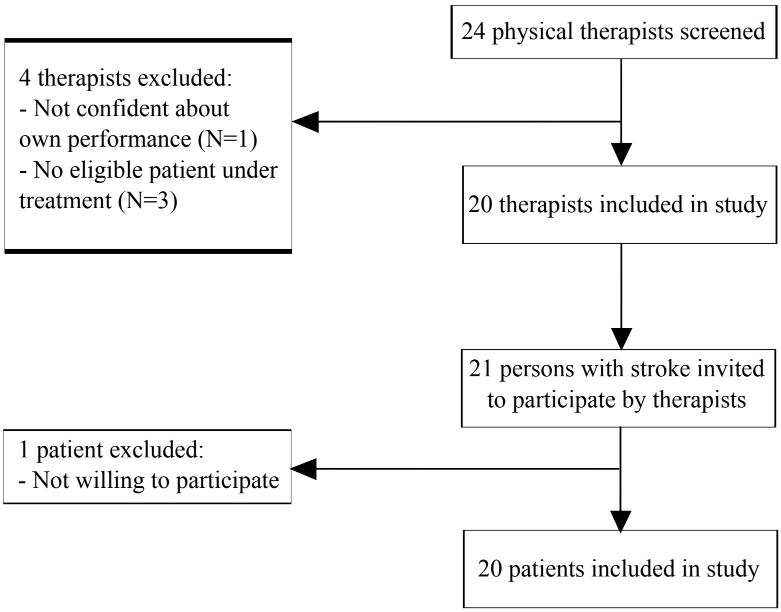


Figure 6.1. Flowchart of inclusion of therapists and patients with stroke.

3.2. Therapy characteristics

Therapy duration ranged from 17.0 to 29.6 minutes (M = 22.7; SD = 3.6), with a total filmed therapy time of 451 minutes. During this time therapists made a grand total of 4821 statements ($M_{statements/session}$ = 241; SD = 60; range = 159-357), averaging out to 10.7 (SD = 2.3) statements per minute (range = 7.4-15.5).

3.3. Nature of statements (Instructions/Feedback/Other)

Figure 6.2 details the nature and attentional focus content of statements for each therapist-patient couple, while Figure 6.3 shows the overall group results. Although results varied considerably across therapists, on average they provided more feedback (M = 37%) than instructions (*M* = 30%). Approximately one-third of all statements were labelled as “other”. These statements often concerned social talk (e.g., about the patients’ weekend, family matters, etcetera), general statements about the overarching goal of the therapy session (e.g., “Today you will practice making transfers”; Therapist-patient couple 16), and also more general conversation about the patient’s progression and rehabilitation goals (e.g., “The main goal when you are back home is to practice walking with the walker in- and outside your house with the neighbour present”; Therapist-patient couple 15). These “other” statements were not further analysed.

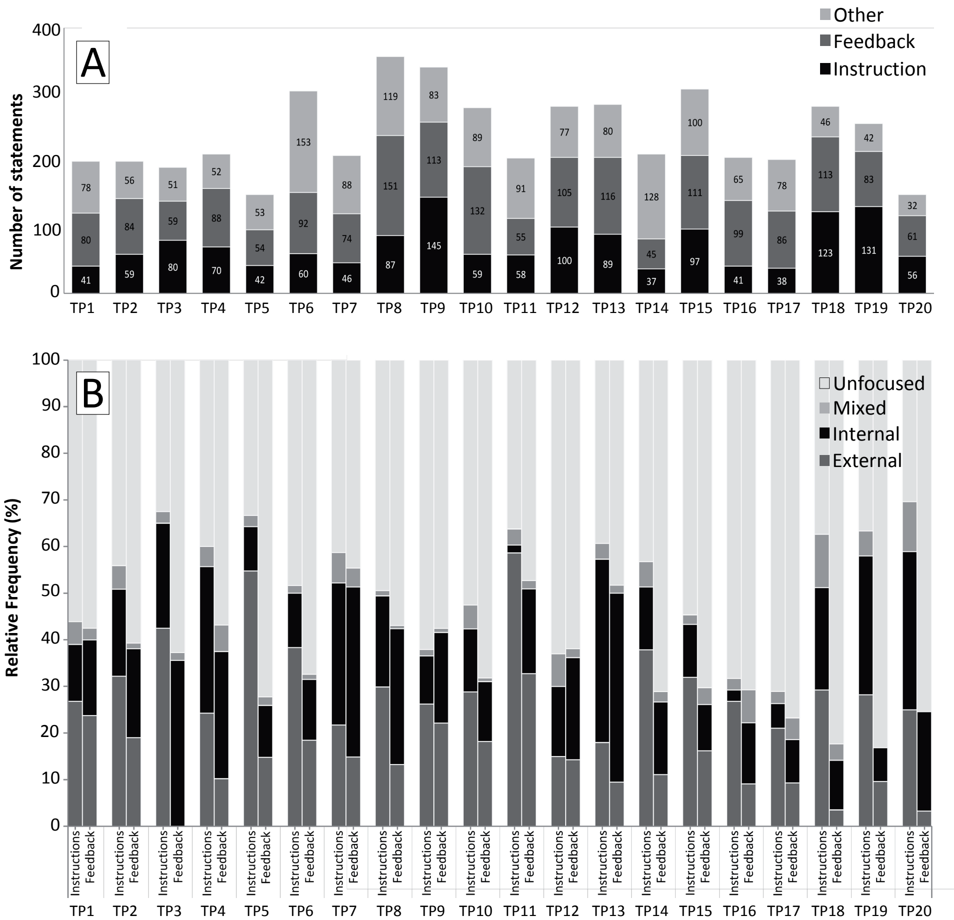


Figure 6.2. Nature (panel A) and attentional focus content (panel B) of statements of each physical therapist. The upper panel (A) shows the total number of instructions, feedback, and other statements. The lower panel (B) depicts what percentage of all instructions (left bar for each therapist-patient couple) and all feedback (right bar for each therapist-patient couple) was external, internal, mixed, or unfocused.

3.4. Attentional focus content of instructions and feedback

Taking a closer look at the attentional focus content of instruction and feedback revealed that therapists' instructions were more often externally focused: on average 19% of all instructions were internal while 30% were external. The subsequent feedback on performance was more often internally focused. Of all feedback statements, 20% had an internal focus, while 14% had an external focus. A typical example is an exercise in which a patient was instructed to "walk around the cones without knocking them over" (external focus), but subsequently received feedback that the "… right foot has difficulty turning inward" (internal focus; Therapist-patient couple 10). Mixed focus statements were infrequently used, both for instructions (4.5%) and feedback (2.3%). Finally, many instructions (46.8%) had no specific focus: i.e., "Start!" or "Go!". Similarly, the high frequency of unfocused feedback statements (64.4%) was due to the large number of motivational statements provided by the therapists. That is, 27.6% of all feedback statements was motivational in nature, such as 'Well done' (Therapist-patient couple 11).

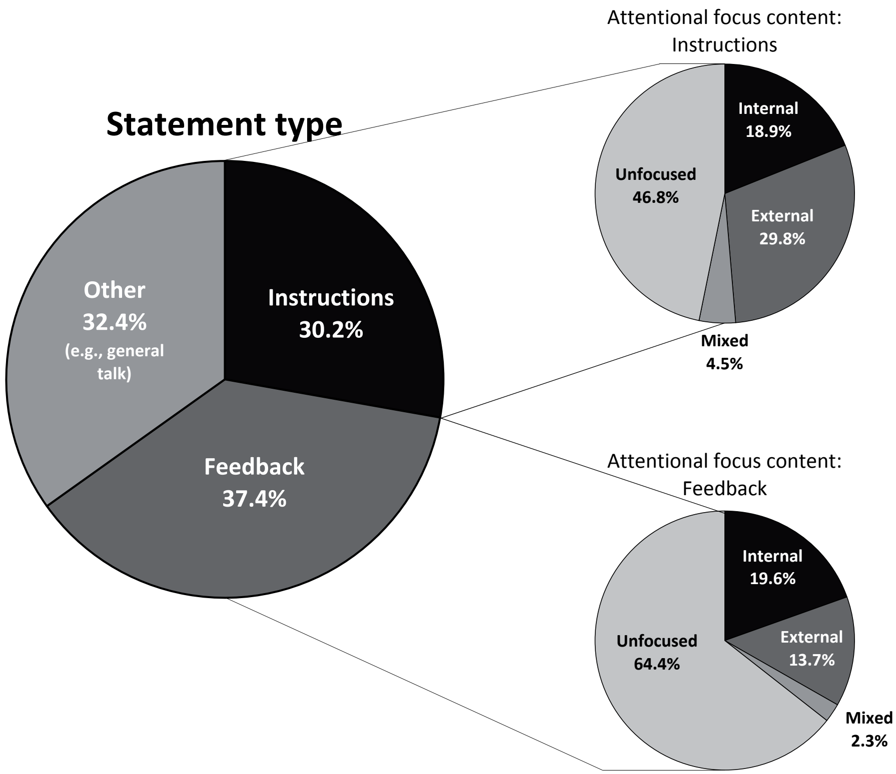


Figure 6.3. Average percentages of instruction, feedback and other statement types (left panel), and average percentages of attentional focus content (right panel) of physical therapists' instruction and feedback.

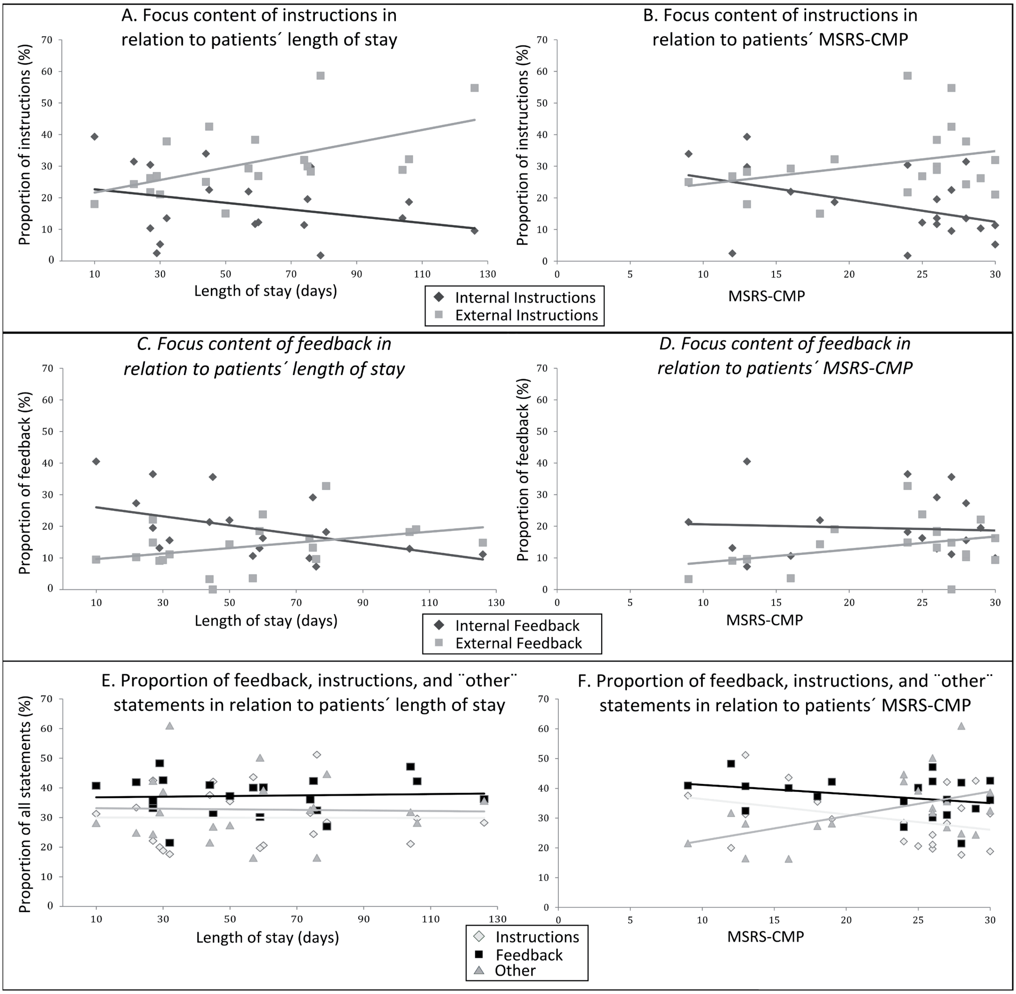


Figure 6.4. Associations between the nature and content of therapists' statements and patients' length of stay and MSRS-CMP scores. Panels A-D depict the relation between the percentages internal and external instructions and feedback on the one hand and patients' length of stay (panels A&C) and MSRS-CMP scores (panels B&D) on the other hand. Panels E-F show the relation between the percentage instructions, feedback, and other statements and patients' length of stay (panel E) and MSRS-CMP scores (panel F). NB: The regression analyses were based on the therapists' relative focus scores (i.e., the relative proportion of external vs. internal statements*100%). In this figure we show the underlying proportions of external/internal focus instructions and feedback for illustrative purposes.

Table 6.2. Characteristics of therapist-patient couples.

Therapist-Patient Couple	Therapist			Patient														
	Gender (m/f)	Age [years]	Experience (years)[a]	Gender (m/f)	Aphasia (yes/no)	Age [years]	Education (0-7)	MoCA [0-30]	MoCA-proxy [0-30][b]	FAC [0-5]	RMI [0-15]	Ambulation Aid[c]	MSRS-CMP [5-30]	MSRS-MS-C [5-30]	Stroke type	Lesion location	Days since admission	Days since stroke[d]
1	f	45	17	m	no	73	4	21	20	4	6	yes	25	10	In	L-Ct	60	65
2	m	37	7	m	yes	56	5	8	2	3	7	yes	19	16	In	L-Ct	106	125
3	m	31	4	f	no	68	5	22	24.5	5	14	yes	27	11	In	L-Ct	45	54
4	f	35	9	m	no	62	3	23	14.5	2	6	yes	28	25	In	R-Ct	22	60
5	f	30	9	m	no	60	5	24	22	3	8	yes	27	18	In	R-Ct	126	136
6	f	50	22	f	no	56	3	16	10	4	9	yes	26	12	In	L-Pons	59	70
7	f	28	5	m	no	40	6	29	28.5	5	14	no	24	17	In	Bi-Ct	27	46
8	f	51	28	m	no	75	6	27	27.5	5	14	yes	26	20	In	R-Ct	75	85
9	m	45	18	m	no	70	6	28	25.5	4	13	no	29	22	In	L-Ct	27	30
10	m	29	6	f	no	56	3	16	17	2	4	yes	26	20	He	L-Sub	104	115
11	f	33	9	m	no	73	5	20	18	3	7	yes	24	18	He	L-Sub	79	87
12	m	54	18	m	no	70	6	24	23.5	0	1	yes	18	16	He	L-CB	50	97
13	f	34	7	f	yes	68	3	12	19.5	2	5	yes	13	9	In	L-Ct	10	57
14	m	56	33	m	no	62	4	24	23.5	4	11	yes	28	15	In	L-Ct	32	****
15	m	33	7	m	no	69	2	23	22	4	10	yes	30	15	He	R-Sub/L-Ct	74	83
16	f	32	7	f	no	68	3	25	25.5	2	3	yes	12	6	In	R-Ct	29	43
17	f	40	16	m	no	67	4	21	24.5	3	7	yes	30	25	In	L-Ct	30	39
18	f	61	38	m	no	60	4	26	18.5	3	5	yes	16	8	In	R-Ct	57	75
19	f	27	2	m	yes	69	2	4	7	4	10	yes	13	17	In	L-Ct	76	95
20	f	31	4	f	no	44	4	28	24.5	1	6	yes	9	28	In	R-Ct	44	61
Mean		39.1	13.3			63.3		21.1	19.9		8.0		22.5	16.4			56.6	74.9
SD		10.2	10.0			9.1		6.6	6.8		3.7		6.5	5.8			30.5	28.6
Median							4			3								
Range							2-6			0-5								

NB: Bi = bilateral; CB = cerebellum; Ct = cortex; FAC=Functional Ambulation Categories; He = haemorrhage; In = infarction; R = right hemisphere; L = left hemisphere; MoCA = Montreal Cognitive Assessment; MoCA-proxy = therapists' judgment of patients' performance on MoCA; MSRS-CMP = Movement-Specific Reinvestment Scale, conscious motor processing subscale; MSRS-MSC = Movement-Specific Reinvestment Scale, Movement Self-Consciousness subscale; RMI = Rivermead Mobility Index; SD = standard deviation; Sub = subcortex

[a] Number of years therapist has been working with people with stroke.

[b] For the memory-item of the MoCA-proxy, therapists had to indicate the number of words they thought the patient would be able to recall correctly, choosing from 0, 1, 2-3, and 4-5 words. As patients scored one point per correctly recalled word, this resulted in non-rounded MoCA-proxy scores in some cases.

[c] I.e., this could refer to any ambulation aid (ankle-foot orthosis, walking cane, rollator, etcetera).

[d] For one patient, the exact stroke date was unknown.

3.5. Relation between therapists' attentional focus use and patient characteristics

Independent linear regression analyses revealed that patients' length of stay in the rehabilitation centre (R^2 = 0.296, B = -0.264, p = 0.013) and MSRS-CMP scores (R^2 = 0.222, B = -1.066, p = 0.036) were independently and negatively associated with therapists' relative focus scores. These associations were maintained when a subsequent multivariate linear regression analysis was run on both these factors (R^2 = 0.462, F(2,17) = 7.30, p = 0.005; $B_{lengthofstay}$ = -0.239, p = 0.013; $B_{MSRS\text{-}CMP}$ = -0.930, p = 0.035). This indicates that therapists gave relatively more externally focused (and fewer internally focused) statements to patients who had spent more time in rehabilitation and who reported a stronger preference for an internal focus. These findings are illustrated by Figure 6.4 in which the association between attentional focus and length of stay/MSRS-CMP scores is shown separately for instructions and feedback (panels A-D).

As discussed earlier, in our sample instructions were more often externally focused, and feedback more often internally focused. Therefore, the results noted above might simply reflect that patients with stronger internal focus preferences and/or longer length of stay received more instructions and less feedback (rather than more externally focused instructions and feedback). As can be seen in Figure 6.4 (panels E-F), this was not the case: the relative proportion of instructions and feedback was similar regardless of patients' length of stay or focus preference. Notably, though, an incidental finding was that therapists gave fewer instructions/feedback and made more "other" statements to patients with higher MSRS-CMP scores (r = .50, p = .03).

No independent associations were found between therapists' predominant focus scores and patient´s MSRS-MS-C, RMI, MoCA, and MoCA/proxy scores (*p's*>.5). Worthy of note, therapists' MoCA-proxy scores did show high agreement with the MoCA scores obtained by the experimenter (ICC = .83).

3.6. Questionnaire results

One therapist could not complete the questionnaire after the therapy session, and failed to respond to follow-up emails. All therapists who did complete the questionnaire (N=19) indicated they were familiar with the concept of internal and external focus of attention. Further, fourteen therapists preferred an external focus in daily practice (i.e., > 2.5 points on the 5-item questionnaire), three did not have a clear preference (score = 2.5), and two preferred an internal focus (score < 2.5). Finally, sixteen therapists stated that they made deliberate choices in their use of external and internal focus strategies in daily practice. Twelve therapists indicated they took patients' cognitive abilities into account, by using more external cues for patients with more severe cognitive impairments. Other factors that were mentioned more than once were patients' rehabilitation phase/motor skill (N=7), learning style (N=6), and body awareness (N=3). More specifically, therapists reported that they made more use of external focus cues in later learning phases, that they tried to tune in to patients' "learning style" (i.e., by finding out which focus works best for which patient, mostly by trial and error), and that they generally preferred to use more internal focus cues for patients with impaired body awareness.

4. Discussion

This study aimed to determine with what frequency physical therapists use internal and external focus instructions and feedback when retraining gait of inpatient individuals with stroke. In addition, we explored whether a patient's internal focus preference, rehabilitation phase, motor skill, and cognition were related to how often therapists used a particular focus strategy. Contrary to our hypothesis, therapists used a balanced mix of external and internal focus strategies, using relatively more externally focused instructions and more internally focused feedback. In addition, therapists made less use of internal focus cues and more of external ones for patients with a stronger internal focus preference and longer length of stay.

The current study's unexpected findings nuance earlier reports that patients with stroke almost exclusively receive internal focus instructions *and* feedback from their therapists.[42,43] It seems unlikely that differences in scoring underlie the considerably higher proportion of external statements in the current study, since our methodology was highly similar to that of the previous studies.[42,43] A more plausible explanation is therapists' preferred focus. In the current study, fourteen out of nineteen therapists indicated that they generally preferred external focus strategies in daily practice. By contrast, in the study of Durham et al.[43] six out of eight therapists preferred a mixed or internal focus strategy. The more pronounced external focus preferences among the current study's therapists may in part be due to the fact that the concept of external/internal focus of attention has received much attention since these previous investigations. Relatedly, our cohort consisted of experienced (M = 13.3 ± 10.3 years) physical therapists specialized in stroke rehabilitation, who regularly participate in neurorehabilitation courses and conferences in which topics such as internal/external focus learning are discussed. Combined, this likely made our cohort more inclined to use an external focus than the therapists in the studies of Durham et al.[43] and Johnson et al.[42] whom were somewhat less experienced ($M_{\textit{Durham}\text{ et al.}}$ = 6.7 ± 3.0 years; $M_{\textit{Johnson}\text{ et al.}}$ = 7.1 ± 3.5 years). Finally, another factor that may explain the difference in results is that fact that the NDT/Bobath method is widely practiced in the UK, while in The Netherlands the emphasis is now on "direct learning of the actual intended functional skill".[251] Arguably, the Bobath approach seems more likely to require an internal focus approach, as it is more directly concerned with achieving a prescribed, desired movement pattern.

Another novel finding of the current study is that therapists' use of instructions and feedback was influenced by specific patient characteristics, namely their focus preference and length of stay. With regard to the former, therapists gave relatively more external focus (and fewer internal focus) cues to patients with a stronger internal focus preference. In addition, these patients also received fewer instructions and less feedback. At first glance, this apparent mismatch between the preferred focus of the patient and the provided focus of the therapist might seem to point at a misjudgement of the therapist. However, combined these findings could also be explained as an attempt of therapists to discourage such "internal focusers" from over-focusing on their movement execution, by giving them less movement-specific and more externally referenced information. Thus, in some cases therapists apparently deviated from their self-reported strategy of tuning in to their patients' preferred focus. This finding provides a specific lead for future research: should therapists adapt to patients' focus habits, or should they prevent patients from relying too much on conscious control? While some recent studies suggest that it may be best to align instructions with an individual's focus preference,[212,215] it has also been argued that a too strong internal focus preference can prevent patients from successfully re-automating motor control.[28] For these patients, using a (non-matching) external focus approach might be preferred. More research is needed to delineate the optimal use of attentional focus in relation to patients' own preferences.

Therapists' relative use of attentional focus was also influenced by the time that patients had spent in inpatient rehabilitation. Patients with a longer length of stay heard more external focus statements, and proportionally fewer internally referenced cues. As our study did not involve a longitudinal observation, we must be careful with interpreting this finding. Still, one gets the impression that therapists use an "internal-then-external" strategy in the course of rehabilitation. This idea is supported by the fact that therapists themselves stated they relied more on external focus strategies in later learning stages. Such an internal-then-external strategy fits classical views on motor learning, which hold that conscious motor control (i.e., an internal focus) is essential for early learning, while strategies that promote more automatic processing (i.e., an external focus[86] become more effective as learning unfolds.[46] The little experimental evidence available seems to provide some initial support for such an approach. One study found that reaching performance of individuals with stroke was optimized when a similar internal-then-external-focus strategy was used,[211] while another recent study suggests that patients with less motor skill show better leg-stepping performance with internal focus than with external focus instructions.[212] Notice, though, that these early findings are purely based on immediate performance effects rather than long term changes as a consequence of learning. In any event, future studies into the overall effects of different focus strategies on motor learning post-stroke may also want to investigate the optimal schedule (both within and across learning sessions) in which attentional focus strategies should be used during motor relearning post-stroke.

Apart from patients' length of stay and focus preferences, no other patient characteristics were associated with the relative frequency with which therapists used external and internal focus instructions/feedback. Especially notable is the absence of such an association with patients' cognitive abilities, considering that most therapists indicated this to be an important factor when choosing for an internal or external focus strategy. Although therapists were able to accurately gauge their patients' cognition (their MoCA-proxy scores highly agreed with those obtained by the experimenter), their use of attentional focus strategies did not seem to be influenced by this knowledge in the current study. It might be that such an association would have been more easily detected if we had observed each therapist with a range of different patients, rather than with one single patient only. Also, the limited statistical power of this study warrants some caution when interpreting lack of statistically significant associations.

A limitation of the current study are that we only observed therapists for one session, and did not incorporate a longitudinal assessment of therapist-patient couples. This may have compromised the reproducibility of our findings. On the other hand, we tried to maximize reliability by observing therapists in a sufficiently long regular therapy session, and with a patient they had already had under treatment. An inherent, yet significant limitation of the current study's observational design is that the mere act of observation may have altered the therapists' and patients' behaviour. This possibility cannot be ruled out, even though we took several precautions to prevent this from happening – i.e., we did not reveal the specific study goal to the participants until after the study was completed, covertly positioned the camera out of sight, and familiarised participants with the experimenter and setting beforehand. Thirdly, the questionnaire we used to determine therapists' preference for/familiarity with internal and external focus of attention had not been officially validated. Fourthly, the use of the MoCA could have resulted in an underestimation of cognitive functioning of the three aphasic patients in our study. A final limitation is the possible presence of selection bias. That is, we studied a relatively small sample of twenty therapists, who selected the patient with which they were observed themselves. Yet, we aimed to minimize this bias by including therapists from 6 different specialized inpatient rehabilitation centres in the Netherlands (out of the 18 existing ones), and including multiple therapists per centre. Also, our patient sample seemed fairly representative for the stroke population as a whole, as they varied considerably in terms of their motor and cognitive abilities.

5. Conclusions

Physical therapists use a mix of relatively more external focus instructions and relatively more internal focus feedback during gait rehabilitation post-stroke. Furthermore, therapists seem to adapt their use of attentional focus strategy to the rehabilitation phase and focus preference of their patients. Future studies may want to specifically test the optimal order in which external and internal focus strategies should be used, and how their use can best be adapted to the individual patient's focus preferences and rehabilitation phase.

Appendix 6.1. Questionnaire on therapists' familiarity with, preference for, and use of external and internal focus of attention.

Instruction: Below are 5 pairs of statements that patients may hear when retraining gait. One statement is internally referenced, and one statement is externally referenced. External statements refer to the outcome or goal of the movement, while internal statements refer to the body and movement execution itself. Please indicate for each pair statements the one that you would **generally prefer** to use in **daily practice** when treating people with stroke. There are no wrong or right answers.

Gait parameter	External	Internal	My preference
Step length	Try to step over the cones	Try to extend your leg more when taking a step	External Internal No preference
Foot clearance	Try not to shuffle during walking	Try to lift your knee properly during walking	External Internal No preference
Standing balance	Place your feet outward	Align your feet with your shoulders	External Internal No preference
Weight bearing transport	Feel the ground "rolling through"	Transfer your weight from your heel to your toes	External Internal No preference
Step width	Try to walk between the lines	Try to walk with your feet in front of each other	External Internal No preference

Were you familiar with this distinction between internal and external focus of attention before this experiment?	Yes / No
In daily practice, do you feel that you make conscious choices in your use of internal and external focus of attention instructions and feedback?	Yes / No
If so, could you specify any reasons/factors that prompt you to use an internal or external focus? (e.g., in terms of patient characteristics, type of exercise, rehabilitation phase, etcetera)	

Chapter 7

External attentional focus enhances movement automatization: A comprehensive test of the Constrained Action Hypothesis

Elmar Kal
John van der Kamp
Han Houdijk

Human Movement Science. 2013;32(4):527-539

Abstract

Background: An external focus of attention has been shown to result in superior motor performance compared to an internal focus of attention. This study investigated whether this is due to enhanced levels of movement automatization, as predicted by the constrained action hypothesis (McNevin, Shea, & Wulf, 2000).

Methods: Thirty healthy participants performed a cyclic one-leg extension-flexion task with both the dominant and non-dominant leg. Focus of attention was manipulated via instructions. The degree of automatization of movement was assessed by measuring dual task costs, as well as movement execution parameters (i.e., EMG activity, movement fluency, and movement regularity).

Results: Results revealed that an external focus of attention led to significantly better motor performance (i.e., shorter movement duration) than an internal focus. Although dual task costs of the motor task did not differ as a function of attentional focus, cognitive dual task costs were significantly higher when attention was directed internally. An external focus of attention resulted in more fluent and more regular movement execution than an internal focus, whereas no differences were found concerning muscular activity.

Conclusions: These results indicate that an external focus of attention results in more automatized movements than an internal focus and, therefore, provide support for the constrained action hypothesis.

1. Introduction

An increasing body of evidence shows that motor performance can be directly influenced by the performer's focus of attention. More specifically, focusing on the effects of movement (i.e., an external focus of attention) has been found to result in superior motor performance compared to focusing on the movement pattern itself (i.e., an internal focus of attention; for comprehensive overviews see[252,253]). McNevin, Shea, and Wulf[254] (see also Wulf[253]) posited the 'constrained action hypothesis' to explain the differential effects of attentional focus on performance. The hypothesis holds that an external focus facilitates motor performance because it promotes automatic control of movement. By contrast, adopting an internal focus of attention induces more deliberate and conscious control of movement, thereby constraining or disrupting 'normal' automatic control processes. The constrained action hypothesis has proven useful in explaining the effects of focus of attention on performance and learning in a wide variety of tasks, such as basketball shooting,[255] balancing,[256] tennis strokes,[257] and jumping.[258] However, most of these studies merely described the effects of attentional focus using relatively simple outcome measures (e.g. accuracy or number of successful attempts). Outcome measures, however, do not easily allow inferences about *how* the two distinct attentional foci effectuate differences in performance. To address this issue, it is necessary to investigate the assumptions of the constrained action hypothesis by assessing to what extent automatization of movement differs as a function of attentional focus. To this end, we aim to measure the effects of attentional focus on automatization of movement in two ways: by assessing dual task interference and through the analysis of movement execution parameters associated with automaticity.

A common method to assess automaticity of movement is investigating the effects of secondary task loading on primary motor task performance.[19] The conjecture is that consciously controlled movements place a substantially higher demand on working memory than automatized movements. Therefore, the execution of a secondary task is expected to interfere with performance on a consciously controlled motor task (i.e., movements performed with an internal focus of attention) but should not – or to a lesser extent – affect performance on an automatized task (i.e., movements performed with an external focus of attention). To date, only a few studies have investigated the effects of attentional focus on dual task performance. In a study by Wulf, McNevin, and Shea[87] adopting an external focus of attention was not only associated with better balancing performance, but also with swifter reactions to auditory stimuli during balancing compared to an internal focus. Similar findings were reported by Poolton, Maxwell, Masters, and Raab.[56] The authors found golf putting performance to be robust to secondary task loading (e.g. a tone counting task) when attention was focused externally, but not when attention was focused internally. Notwithstanding these promising results (cf.[259]), a limitation of these studies is that they did not control for differences in task prioritization in dual task conditions. That is, dual task performance was not corrected for differences in baseline (single task) performance. By contrast, this study assessed dual task costs (DTCs[14]) of both the primary motor and secondary cognitive task.

An alternative approach to assess movement automatization is the analysis of movement execution related parameters that indicate to what extent movements are under automatic or conscious control. One such parameter is electromyographic (EMG) activity. The rationale is that if task execution is consciously controlled this results in more EMG activity than when the task is performed automatically, since the latter constitutes a more efficient mode of motor control.[258] Indeed, a few studies reported that an internal focus led to significantly higher EMG activity than an external one (e.g.[99,255,258]). Two additional parameters that have been frequently discussed in motor control literature with respect to movement automatization – but have not yet been applied in the context of the constrained action hypothesis – are *fluency of movement* (e.g.[260]) and *movement regularity* (e.g.[261]). With regards to fluency of movement, the rationale is that in the course of acquiring a motor skill, the fluency with which a movement is performed increases (e.g.[260,262,263]). This can be illustrated by contrasting the fluent and smooth drive of elite golf players with the more rugged and rigid movements of novice players, reflecting a high degree of conscious control.[264] Fluency of movement is commonly operationalized with the dimensionless jerk, which is derived from the minimal jerk model[265,266] and defined as the rate of change of acceleration of the moving limb. Lower dimensionless jerk values are indicative of higher movement fluency. Movement regularity is operationalized using sample entropy (SEn[267]), a measure which is derived from the theory of stochastic dynamics. For static tasks such as balancing, a *higher* SEn (i.e., lower regularity) is indicative of more automatized movements (e.g.[10,261,268]). However, for cyclical, dynamic tasks such as walking a *lower* SEn (i.e., a higher regularity) is proposed to be indicative of more automatized movements (e.g.[269–271]).

The aim of this study is to test the constrained action hypothesis in a comprehensive manner. To this end, we investigated whether an external focus of attention leads to superior motor performance compared to an internal focus of attention, and, if so, whether this is due to a higher degree of automatization of movement as predicted by the constrained action hypothesis. Healthy participants performed a cyclic one-leg extension-flexion task with both an internal and an external focus of attention. Motor performance was measured through movement duration. Automaticity of movement was assessed in two ways. First, we assessed dual task cost[14] as a function of attentional focus. For this purpose, participants performed the motor task concurrently with a letter fluency task.[272] Second, automaticity of movement was measured by assessing the EMG activity of knee flexors/extensors, the dimensionless jerk of the lower leg and the SEn of the lower leg's anterior-posterior accelerations.

We hypothesized that motor performance would be superior for the external compared to the internal focus conditions. Furthermore, it was expected that this difference in motor performance would be due to a higher degree of movement automatization for trials performed with an external compared to an internal focus of attention. Therefore, dual task costs for both motor and cognitive task performance were expected to be low when attention is focused externally relative to when attention is focused internally. With regards to the three movement execution parameters, it was expected that EMG and dimensionless jerk would be lower when an external focus was adopted. Taking into account the dynamic nature of the cyclic leg movement task,[270] the same pattern was expected for SEn. To independently verify the effects of automaticity on EMG, jerk, and SEn, the motor task was performed with both the dominant and non-dominant leg. We assumed that the dominant leg would induce more automatic motor control whereas that the non-dominant leg would induce more consciously controlled movements with the measures of automatization differing accordingly.

2. Methods

2.1. Participants

A total of 31 volunteers (11 male, 20 female) participated in the experiment. Mean age was 25.06 ± 6.8 years. All participants were healthy and had no problems with speech. All participants signed an informed consent. The protocol of the experiment was approved by the ethical committee of the Faculty of Human Movement Sciences of VU University Amsterdam.

2.2. Equipment and data collection

Participants sat in a chair, in front of which (at approx. 25 cm) a line was taped to the floor in external focus conditions (Figure 7.1). Positioning of the line was adjusted such that participants could place the foot on the line when they flexed the knee approximately 90 degrees. For the letter fluency task a notebook was used to record all words named by the participants. Leg dominance was assessed with the Waterloo Footedness Questionnaire-Revised (WFQ-R[273]). Activity of the m. rectus femoris (RF), m. vastus lateralis (VL), and m. semitendinosus (SET) was recorded with paired bipolar surface EMG electrodes (Ag/AgCL, 2 cm centre-to-centre, 1 cm^2 recording area, Ambu Blue Sensor, type N-00-S). Placement of electrodes and preparation of the target location was in accordance with the SENIAM recommendations.[274] Data were sampled at 1000 Hz. Optotrak 3020 (Northern Digital Inc., Waterloo Ontario) was used to record the movements of the lower leg. LED markers were attached to the malleolus lateralis and halfway an imaginary line from the epicondylus lateralis to the malleolus lateralis of both legs. The Optotrak xyz-coordinate system was defined such that the x-axis pointed forwards (i.e., in the anterior-posterior plane), the y-axis pointed sideward (i.e., in the medio-lateral plane), and the z-axis pointed upwards (i.e., in the transversal plane). Sampling frequency was 100 Hz.

2.3. Experimental design

2.3.1. Experimental tasks

The motor task was a single leg movement task (Figure 7.1), for which participants were required to alternately flex and extend the leg at a comfortable pace for 60 seconds in a sitting position. No performance-optimizing criterion (e.g. move as fast possible) was given, even though this is habitually done in this area of research (e.g.[252,256]). The main reason for doing so is that motor tasks performed in daily life typically require comfortable rather than best performance. Nevertheless, comfortable pace can also be regarded as a performance characteristic. For instance, increases in comfortable walking speed are considered to reflect superior motor performance (e.g. the 10 meter timed walk [224,275]).

Figure 7.1. Motor Task. The left panel shows the external focus of attention condition, in which a line is placed on the floor, while the right panel illustrates the internal focus of attention condition.

The cognitive task was a letter fluency task, for which participants were required to name as many unique Dutch words as possible starting with a certain letter within a limited amount of time (i.e., in this experiment 1 minute). Nine letters with similar level of difficulty were chosen based on Schmand et al.[272]: D-A-T-K-O-M-P-G-R.

2.3.2. Procedure

Participants first completed the WFQ-R to assess leg dominance. Subsequently, two familiarisation trials of motor performance – one for each leg were conducted. Participants did not receive instructions regarding attentional focus for these familiarisation trials. This was followed by a baseline assessment of the letter fluency task. After the familiarisation trials, participants performed two blocks of four trials: one single (ST) and one dual task (DT) trial for each leg. Participants performed the first block with one focus of attention, whereas the second block was performed with the other focus of attention. Focus was manipulated via standardized instructions given prior to the start of the trial, which were repeated shortly every 20 seconds to ensure compliance. To induce an internal focus of attention, participants were instructed to focus on flexing and extending their leg, whereas an external focus of attention constituted an instruction to focus on alternately placing the foot in front of and behind the line. Trials within a block were separated by 2 minutes of rest and blocks were separated by 10 minutes of rest, in which the participant was required to solve a Swedish puzzle. This distraction task was incorporated to minimize the likelihood that the focus of attention in the first measurement block did transfer to the second block. After completion of the second block, performance on the letter fluency task was assessed again to investigate the existence of a learning effect. Both the order of the two blocks (i.e., external versus internal focus of attention) and the order of conditions within blocks (ST versus DT and dominant versus non-dominant leg) were counterbalanced across participants. For each letter fluency trial, participants were given a different letter, the order of allocation of which was randomized.

2.4. Data analysis

Optotrak and EMG data were analysed with customized Matlab programs (Mathworks, Natick MA, USA). For all trials, only data between the first and last three full movement cycles were used for analysis.

2.4.1. Motor performance & dual task costs

Motor performance was defined as movement duration. Median movement cycle duration was calculated for each trial (in seconds), with shorter duration indicating better performance. Heel strikes were identified in the Optotrak data to assess MCD. Cognitive performance was defined as the number of words named per trial. To identify the dual task interference on both tasks, dual task costs (DTCs[14]) were calculated for both motor and cognitive tasks using equation 5.2:

Thus, deterioration in performance in DT conditions is reflected by a higher DTC.

2.4.2 Movement execution related variables

2.4.2.1. EMG

EMG was amplified, and filtered online using a 10-400 Hz Butterworth bandpass filter. The raw EMG data were full-wave rectified and smoothed with a bidirectional, band-pass, fourth-order Butterworth filter (cut-off frequency 25-200 Hz). After rectification of the signal, the average EMG activity of the RF, VL, and ST was calculated resulting in the mean EMG amplitude (in mV) for each muscle per trial.

2.4.2.2. Dimensionless jerk

Optotrak data were filtered bidirectional, using a fourth-order Butterworth filter. The cut-off frequency was set at 6 Hz after inspection of the power-spectral density plot of several randomly selected trials. Data of the marker attached halfway at the lower leg were used. Dimensionless jerk[264] was assessed as follows: first, the resultant acceleration was calculated from the position data. For each movement cycle, this resultant acceleration was normalized by dividing it by its mean. Next, the derivative of this normalized acceleration was calculated. However, since differences in movement duration will influence this step, the mean rectified jerk per movement cycle was calculated and multiplied with movement duration. The median of the resultant dimensionless jerk for all movement cycles was then calculated to determine the dimensionless jerk for the whole trial.

2.4.2.3. SEn

SEn is quantified as "the negative natural logarithm of the conditional probability (CP = A/B) that a dataset of length N, having repeated itself within a tolerance *r* for *m* points, will also repeat itself for *m* + 1 points, without allowing self-matches".[261 (p. 206)] In this equation, B represents the total number of matches of length *m*, and A represents the total number of matches of length *m*+1. SEn is then assessed with –log(A/B). Consequently, more regular time series are indicated by lower SEn. SEn was calculated for the anterior-posterior acceleration of the same marker used for jerk analysis after parameter selection (i.e., *m* and *r*) was optimized in line with recommendations of Lake et al.[276] This resulted in *m* = 3 and *r* = .03 as parameter settings.

2.5. Statistics

All statistical analyses were executed using SPSS version 18.0 (PASW Statistics, 2011). Motor performance outcome scores were first analysed with a repeated measures ANOVA with Focus (external vs. internal) and Side (dominant vs. non-dominant) as within factors. Dual task performance was analysed with a 2(Focus) x 2(Side) x 2 (Task: motor vs. cognitive task) repeated measures ANOVA on motor and cognitive DTCs. To investigate automatization of movement, EMG results were analysed with a paired samples t-test for each muscle separately, whereas dimensionless jerk and SEn data were analysed with a 2(Focus) x 2(Side) repeated measures ANOVA. Significant effects were followed up using Bonferroni-adjusted t-tests. For ANOVA's, effect sizes were calculated with partial eta squared (η_p^2), with values of 01, .06, and .14 indicating small, medium, and large effect sizes respectively.[277]For t-tests, effect sizes were assessed with Cohen's *d*, with .2, .5, and .8 representing small, medium, and large effect sizes respectively.[278] Significance level was set at $p = .05$.

3. Results

Thirty participants completed the experiment successfully. One male participant was excluded because of non-compliance with the instructions. Results of the WFQ-R revealed that 26 of the remaining 30 participants were right-footed.

3.1 Motor performance

Analysis of variance revealed a large main effect of Focus ($F(1,29) = 13.7$, $p < 0.01$, $\eta_p^2 = 0.32$): Movement duration was significantly shorter when an external focus was adopted (M = 1.25 s, SEM = 0.05 s) than when attention was focused internally (M = 1.31 s, SEM = 0.05 s). No main effect of Side ($F(1,29) = 0.7$, $p = 0.4$) and no interaction of Focus and Side ($F(1,29) < 0.1$, $p > 0.8$) was found.

3.2. Automatization of movement

To investigate to what extent the beneficial effects of an external focus on motor performance were related to increased automatization of movement, the effects of performing a concurrent secondary task will be reported first, followed by results for the parameters related to movement execution.

3.2.1. Dual task cost

The DTCs (in percentages) for the motor and the cognitive tasks are illustrated in Figure 7.2. This shows that ST motor performance was maintained at the expense of cognitive task performance when an internal focus of attention was adopted, whereas no dual task interference was apparent when an external focus was adopted. This effect seemed more pronounced for the non-dominant leg.

Accordingly, the analysis of variance revealed a large significant main effect of Focus ($F(1,29) = 7.4$, $p < 0.05$, $\eta_p^2 = 0.20$), indicating that DTCs were indeed higher in the internal compared to the external focus conditions. The main effects of Task ($F(1,29) = 3.7$, $p = 0.06$, $\eta_p^2 = 0.11$), Side ($F(1,29) = 3.1$, $p = 0.09$, $\eta_p^2 = 0.10$) and the interaction effects of Focus x Side ($F(1,29) = 4.2$, $p = 0.08$, $\eta_p^2 = 0.10$) and of Focus x Side x Task ($F(1,29) = 3.2$, $p = 0.08$, $\eta_p^2 = 0.10$) failed to reach significance, but had medium sized effects. The interaction effect of Focus and Task ($F(1,29) = 15.8$, $p < 0.01$, $\eta_p^2 = 0.34$) did reach significance however, and was of large effect size. Post hoc tests indicated that cognitive DTCs were higher for the internal compared to the external focus conditions ($t(29) = 3.4$, $p < 0.01$, $d = 0.70$), whereas motor DTCs were lower for the internal compared to external focus conditions ($t(29) = 2.6$, $p < 0.05$, $d = 0.48$).

Finally, Bonferroni corrected one sample t-tests were used to examine if DTCs were larger than zero. Neither motor ($t(29) \leq 1.8$, $p > 0.6$) nor cognitive DTCs ($t(29) < 0.4$, $p = 1$) significantly exceeded zero when an external focus of attention was adopted. An internal focus of attention did not result in motor DTCs that significantly differed from zero either ($t(29) < 0.4$, $p = 1$). However, focusing internally did result in cognitive DTCs larger than zero for trials performed with the non-dominant leg ($t(29) = 6.1$, $p > 0.01$, $d = 1.57$, 95% CI = [10.2%, 26.2%]), but not with the dominant leg ($t(29) = 2.6$, $p = 0.11$, $d = 0.68$, 95% CI = [-0.08%, 19.2%]).

In sum, although motor DTCs were somewhat higher when an external compared to an internal focus of attention was adopted, motor task performance remained similar in dual compared to single task conditions, irrespective of attentional focus. However, an internal focus of attention resulted in a deterioration of cognitive task performance, especially in trials performed with the non-dominant leg.

3.2.2. Movement execution related parameters

EMG (in mV), dimensionless jerk, and SEn in the single motor task condition are displayed in Figures 7.3, 7.4, and 7.5. With regards to dimensionless jerk and SEn, it was first investigated whether differences existed between trials performed with the dominant or non-dominant leg to verify the effect of automaticity on these variables. This analysis was not possible for the EMG data, since no measurements of maximal voluntary contraction were conducted and non-normalized EMG values of different muscles cannot be compared. For each variable, it was assessed whether differences existed between external and internal focus conditions.

3.2.2.1. EMG

Although EMG activity was generally higher in the external compared to the internal focus conditions (see Figure 7.3), Bonferroni-corrected paired samples t-tests revealed that these differences were not significant (t's$(29) < 2.4$, p's > 0.10); muscular activity was not different between focus conditions.

3.2.2.2. Dimensionless jerk

Analysis of variance revealed a trend towards a significant main effect of Side of medium effect size ($F(1,29) = 4.1$, $p = 0.053$, $\eta_p^2 = 0.12$). This indicated that the dominant leg produced more fluent movements compared to the non-dominant leg. The large main effect of Focus ($F(1,29) = 6.1$, $p < 0.05$, $\eta_p^2 = 0.18$) indicated that movement execution was more fluent when attention was focused externally as opposed to internally (see Figure 7.4).

3.2.2.3. Sample entropy

Analysis of variance revealed a large main effect of Side ($F(1,29) = 7.1$, $p < 0.05$, $\eta_p^2 = 0.20$), which indicated that movement execution was of higher regularity when movements were performed with the dominant compared to the non-dominant leg. The large main effect of Focus ($F(1,29) = 9.5$, $p < 0.01$, $\eta_p^2 = 0.25$) was due to the fact that an external focus resulted in higher movement regularity compared to an internal focus of attention (see Figure 7.5).

In sum, an external focus of attention resulted in more fluent and more regular movement execution than an internal focus of attention. Muscular activity did not differ between these focus conditions. The dominant leg produced more fluent and more regular movements than the non-dominant leg.

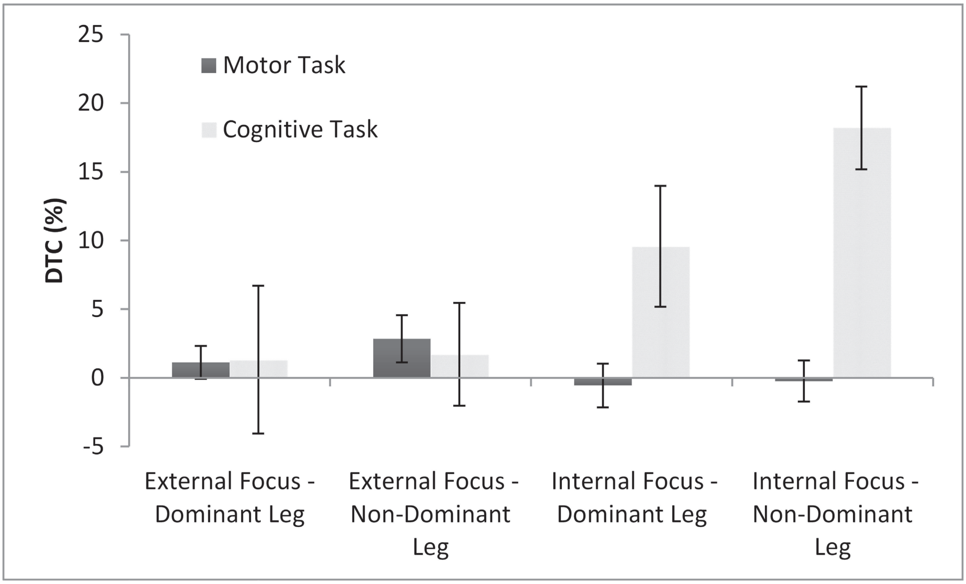


Figure 7.2. Average DTC scores as a function of task, focus, and side ± SEM. Scores are in percentages, with positive and negative values indicating increment and decrement, in dual task costs respectively.
NB: EFA = External focus of attention; IFA = Internal focus of attention; DOM = Dominant leg; NDOM = Non-dominant leg.

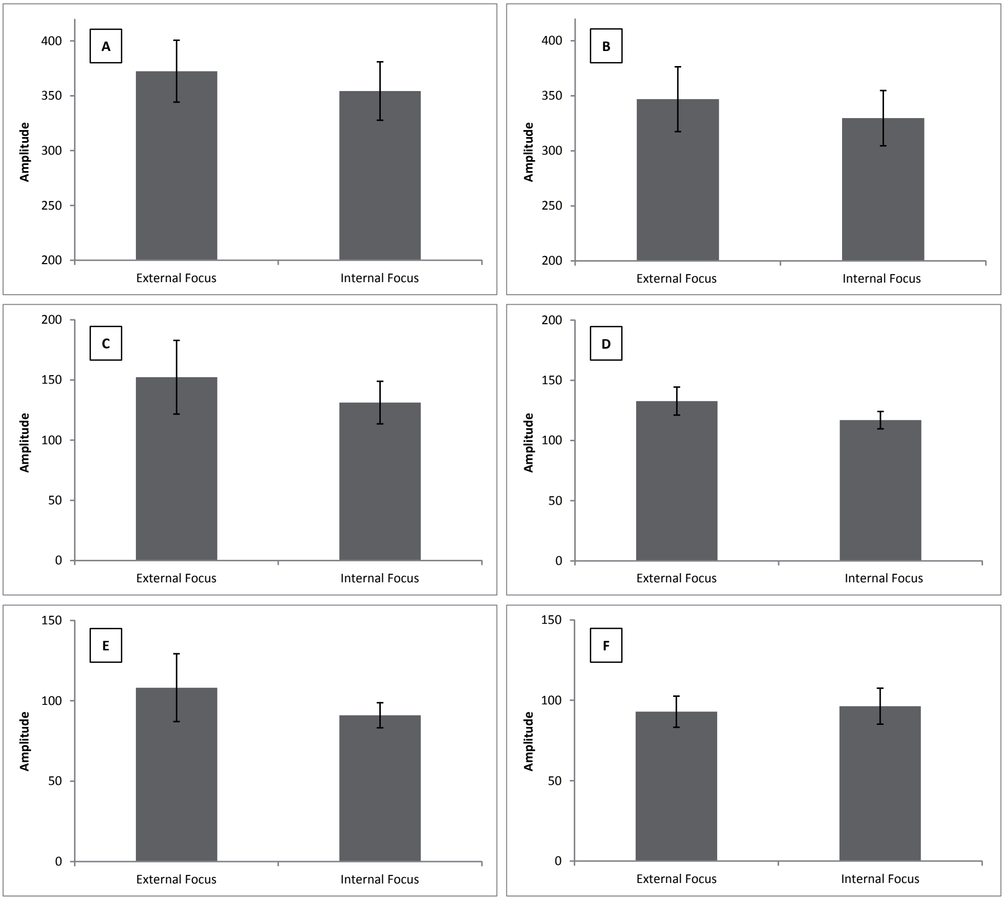


Figure 7.3. Average EMG amplitude ± SEM for the single task conditions. EMG amplitudes are displayed for the m. rectus femoris, m. vastus lateralis, and m. semitendinosus of the dominant (A, C, and E respectively) and non-dominant leg (B, D, and F, respectively).

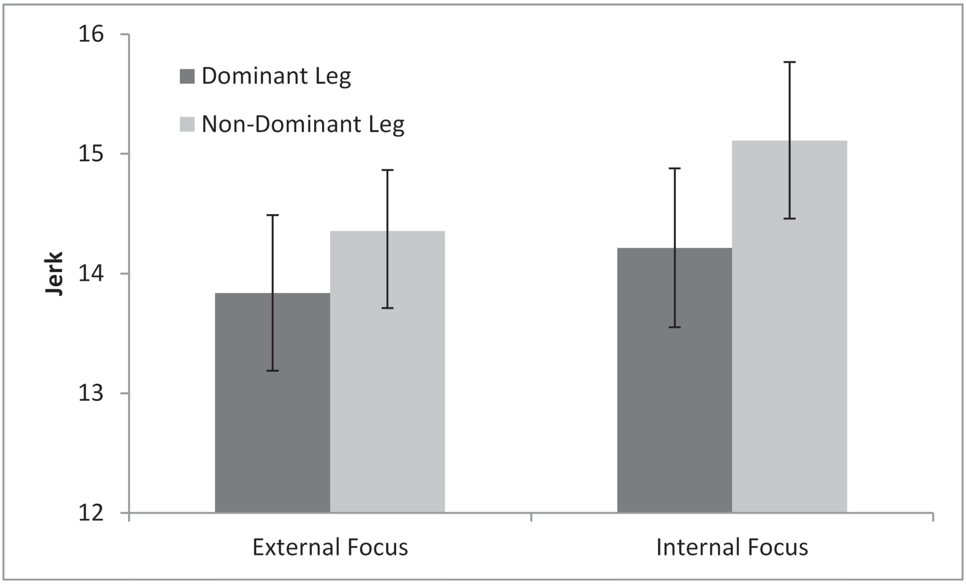


Figure 7.4. Average dimensionless jerk ± SEM for the single task conditions.

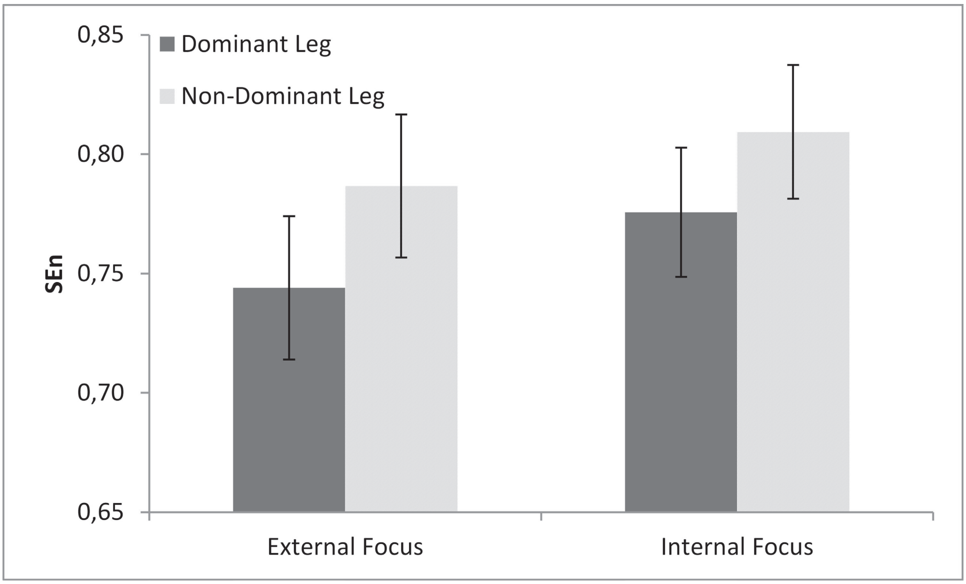


Figure 7.5. Average SEn ± SEM for the single task conditions.

3.3. Effects of secondary task loading on movement execution related parameters

Although, it was not a specific aim of this study, its design also allowed us to explore the effect of secondary task loading EMG, dimensionless jerk, and SEn as a function of focus. To this end, we conducted six 2(Focus) x 2(Task: ST vs. DT) ANOVAs to analyse the EMG results of each muscle, and two 2(Focus) x 2(Side) x 2(Task) ANOVAs for the analysis of dimensionless jerk and SEn data. Only main and interaction effects of Task (i.e., comparing single and dual task outcomes) are reported, so as to not duplicate the effects discussed above.

Analyses of EMG data revealed a significant main effect of Task for the RF of both the dominant ($F(1,29) = 16.5$, $p < 0.001$, $\eta_p^2 = 0.36$) and non-dominant side $F(1,29) = 12{,}9$, $p < 0.01$, $\eta_p^2 = 0.31$) as well as for the dominant SET ($F(1,29) = 7.5$, $p < 0.05$, $\eta_p^2 = 0.21$). These effects indicated that muscular activity was significantly lower in DT compared to ST conditions with regards to the dominant RF (M = 363.4 mV, SEM = 26.5 mV vs. M = 323.6 mV, SEM = 23.4 mV, for ST and DT trials respectively), non-dominant RF (M = 338.3 mV, SEM = 26.8 mV vs. M = 318.0 mV, SEM = 26.8 mV, for ST and DT trials respectively), and dominant SET (M = 99.6 mV, SEM = 11.9 mV vs. M = 92.7 mV, SEM = 11.9 mV, for ST and DT trials respectively), but not for the non-dominant SET or VL of either leg. No interactions of Focus and Task were found for either muscle ($F(1,29) < 0.9$, $p > 0.3$).

In contrast to the EMG results, analysis of the dimensionless jerk results did not reveal significant (interaction) effects of Task (F's(1,29) < 3.9, p's > 0.07). Thus, movement fluency was not significantly different in DT compared to ST conditions.

With regards to third variable, SEn, only a significant interaction between Side and Task was found with a large effect ($F(1,29) = 5.22$, $p < 0.05$, $\eta_p^2 = 0.16$). Post-hoc testing revealed a non-significant increase in movement regularity in DT (M = 0.736, SEM = 0.027) compared to ST (M = 0.760, SEM = 0.028) conditions for the dominant ($t(29) = 2.34$, $p = 0.051$, d = 0.43, 95% CI = [-0.000, 0.047]) but not for the non-dominant leg (M = 0.796, SEM = 0.029, and M = 0.798, SEM = 0.027 for DT and ST conditions, respectively; t's(29) < 0.2, p's > 0.8). Hence, SEn values indicated that secondary task loading might enhance automatization, but only for movements performed with the dominant leg.

4. Discussion

The present study investigated the constrained action hypothesis. To this end, it was assessed whether performance benefits associated with an external compared to an internal focus of attention were due to differences in automatization of movement. We used the typical approach to measuring automaticity – a dual task paradigm – as well as independently obtained measures of automaticity by measuring variables that reflect movement execution: EMG, dimensionless jerk (fluency of movement), and SEn (movement regularity).

Congruent with previous studies,[252,253] we found an external focus of attention to result in superior motor performance (i.e., shorter movement duration) compared to an internal focus of attention. Assessment of dual task interference indeed revealed that this was likely due to enhanced automaticity of movement. In agreement with earlier work on this topic,[56,87] interference seemed to occur only when an internal focus of attention was adopted whereas performance remained robust when attention was focused externally. Different from these studies, however, secondary task loading interfered with performance on the cognitive task only and not with performance on the motor task. This most probably reflected good compliance of participants to the instruction to prioritize performance on the leg movement task. However, maintaining motor task performance was at the expense of cognitive task performance when attention was focused internally, an effect that was most pronounced for the (presumably) least automatized non-dominant leg. This supports the constrained action hypothesis in that an external attentional focus seems to reduce the attentional capacity required for movement execution compared to an internal one. It also shows the importance of considering the DTCs of the second task as well, something which earlier studies did not address.[56,87,259]

From a practical point of view, dual task interference is of special interest to patients with acquired brain injury (ABI), since many experience significant problems with the concurrent performance of multiple tasks (e.g.[14,279]). This may – partially – be related to an increased tendency to focus on movement execution.[28] Impairments in dual task performance limit successful daily functioning and have been associated with an increased risk of falls.[279] The current results of this study may imply that shifting the focus of attention of ABI patients away from movement execution and towards movement effects might be an efficacious intervention to address this problem. However, considering the differences in motor skill, (heterogeneity of) neurological damage, and cognitive impairments, more experimental work is needed to assess whether the effects of attentional focus on motor and motor-cognitive task performance in ABI patients are indeed similar as observed here in healthy adults.

Additional evidence for the constrained action hypothesis is provided by the analysis of the movement execution related parameters in the single motor task condition. Dimensionless jerk and SEn results showed that an external relative to an internal focus of attention resulted in more fluent movements of higher regularity, which is in accordance with studies that have found both movement fluency (e.g.[260,262,263]) and regularity (e.g.[269–271]) to increase as a function of motor skill and automatization. The fact that both dimensionless jerk and SEn accurately differentiated between the dominant and non-dominant leg provides further support for the validity of these variables. Of note, in contrast to several studies (e.g.[99,255,258]), EMG activity was similar regardless of attentional focus. However, since an external focus of attention resulted in significantly faster motor performance but similar levels of muscular activity, this may actually indicate that an external focus of attention induces more efficient movement control and hence reflect a higher degree of automatization. This explanation is in line with earlier work that suggested that an internal focus of attention may result in less efficient (inter)muscular coordination compared to an external focus of attention.[99,258,280] In sum, the EMG, dimensionless jerk, and SEn results support the constrained action hypothesis: an external focus leads to more automatized movements than an internal one. Nonetheless, the constrained action hypothesis does not specify *what* exactly is constrained by adopting an internal focus of attention,[281,282] the present findings are largely inconclusive on how an internal focus disrupts movement automaticity. This remains a critical issue for future work.

Brain imaging is another important avenue for research that may further enhance understanding the effects of attentional focus. Currently, not many studies have explicitly investigated the differences in neural substrates between movements performed with an internal or external focus, but preliminary work suggests that an internal focus results in reduced activity of the primary motor and somatosensory cortex compared to an external focus.[283] Furthermore, increased activation of the prefrontal cortex indicates that conscious control of movement relies on executive function to a greater extent than automated motor performance.[284] Increased involvement of analytical processing is consistent with results of studies that applied electroencephalography (EEG). Specifically, automatization of movement has been related to the degree to which verbal-analytical brain areas of the left-hemispheric temporal lobe show synchronized activation with motor planning regions in the right hemisphere (i.e., premotor cortex; e.g.[285]): higher levels of synchronization or coherence reflect increased conscious control of movement. Recently, Zhu and colleagues have shown that implicit or incidental motor learning results in less synchronization compared to when motor learning is conscious and under executive control (e.g.[68,69]). Future studies should assess whether lower levels of synchronization between verbal and motor areas are also characteristic for external versus internal focus of attention. This would not only provide insight into the constrained action hypothesis but would also yield information regarding the possible common neural substrate underlying the concepts of implicit motor learning and learning with an external focus of attention (see also [56]).

A final note concerns the results of the exploratory analyses into the effect of secondary task loading on movement execution. Our findings indicated that differences existed in movement automatization between ST and DT trials. That is, EMG activity and SEn of trials performed with the dominant leg were lower during ST than during DT performance, whereas for dimensionless jerk no differences were found. This suggests that movement execution tended to show an increased level of automatization under secondary task loading relative to single motor task performance. First, with respect to the constrained action hypothesis, it is pertinent to note that these differences in movement automatization between ST and DT were not mediated by attentional focus. Second, although there were clear costs (i.e., degraded performance of the cognitive task) when concurrently performing two tasks, secondary task loading does appear to have enhanced movement automatization. There is no straightforward explanation for these findings. Possibly, the secondary task prevented any conscious control of the leg flex and extension movement, thereby in fact increasing automatization (see e.g.[286]). Clearly, more work is needed to better understand the effects of secondary task loading on movement automatization.

5. Conclusion

To conclude, this study showed that an external focus of attention resulted in superior motor performance compared to an internal focus. Assessment of dual task performance, EMG activity, movement fluency, and movement regularity indicates that this is due to an external focus of attention promoting more automatized movements than an internal focus, as is predicted by the constrained action hypothesis.

6. Acknowledgements

We thank Elizabeth Wemmenhove for her contributions in the preparatory phase of this study and the drawing of Figure 7.1.

Chapter 8

Stay focused! The effects of external and internal focus of attention on movement automaticity in people with stroke

Elmar Kal
John van der Kamp
Han Houdijk
Erny Groet
Coen van Bennekom
Erik Scherder

PloS One. 2015;10(8):e0136917

Abstract

Background: Dual-task performance is often impaired after stroke. This may be resolved by enhancing patients' automaticity of movement. This study sets out to test the constrained action hypothesis, which holds that automaticity of movement is enhanced by triggering an external focus (on movement effects), rather than an internal focus (on movement execution).

Methods: Thirty-nine individuals with chronic, unilateral stroke performed a one-leg-stepping task with both legs in single- and dual-task conditions. Attentional focus was manipulated with instructions. Motor performance (movement speed), movement automaticity (fluency of movement), and dual-task performance (dual-task costs) were assessed. The effects of focus on movement speed, single- and dual-task movement fluency, and dual-task costs were analysed with generalized estimating equations.

Results: Results showed that, overall, single-task performance was unaffected by focus (p = 0.341). Regarding movement fluency, no main effects of focus were found in single- or dual-task conditions (p's ≥ 0.13). However, focus by leg interactions suggested that an external focus reduced movement fluency of the paretic leg compared to an internal focus (single-task conditions: p = 0.068; dual-task conditions: p = 0.084). An external focus also tended to result in inferior dual-task performance (β = -2.38, p = 0.065). Finally, a near-significant interaction (β = 2.36, p = 0.055) suggested that dual-task performance was more constrained by patients' attentional capacity in external focus conditions.

Conclusions: We conclude that, compared to an internal focus, an external focus did not result in more automated movements in chronic stroke patients. Contrary to expectations, trends were found for enhanced automaticity with an internal focus. These findings might be due to patients' strong preference to use an internal focus in daily life. Future work needs to establish the more permanent effects of learning with different attentional foci on re-automating motor control after stroke.

1. Introduction

Performing two or more tasks at the same time is integral to daily functioning. During the day, we frequently need to perform motor tasks like walking and grasping in combination with all sorts of cognitive (e.g., making a phone call, monitoring the traffic while crossing the street, memorizing a shopping list) or motor (e.g., carrying a tray) tasks. While healthy adults generally achieve this with ease, performing dual-tasks is often far more difficult for stroke patients, as their gait and balance often remain highly susceptible to interference from secondary cognitive task performance.[8] This increased dual-task interference may affect patients' mobility, and has been linked to an increased risk of falling.[17,287]

The challenge for clinicians therefore is to find ways to reduce patients' dual-task interference. Successful dual-task performance depends on an individual's working memory capacity.[22] Typically, it is assumed that during dual-tasking, each task consumes a share of working memory capacity. If the combined processing demands of two tasks exceed the capacity of working memory, dual-task interference will occur and performance on either or both these tasks will deteriorate.[19] Therefore, one way to improve dual-task performance is to reduce the demands placed on working memory, for instance, by increasing automaticity of movement.

Reducing the working memory processing demands of motor tasks may be achieved by manipulating the attentional focus of performers. Evidence from healthy adults shows that motor performance and learning are superior when performers focus on the outcome of their movements (i.e., an external focus) rather than on movement execution itself (i.e., an internal focus; for a review see[57]). According to the constrained action hypothesis[254] this is due to the fact that an external focus promotes automatic motor control, whereas an internal focus triggers conscious control of movement. In support of this hypothesis, an external focus has indeed been found to result in more automated movement execution in healthy participants, as evidenced by more efficient neuromuscular control (e.g., less muscular activity and co-contraction[99,255,288]) and more fluent and regular movement execution.[86] In line with the notion that enhanced movement automaticity reduces the demand for working memory resources,[44,204] an external focus also results in superior dual-task performance.[56,86,87]

Observational studies have suggested that stroke patients primarily receive internally referenced instructions and feedback during rehabilitation therapy.[43,178] Also, many patients remain prone to use an internal focus to control their movements up to years after discharge.[28] If the evidence for the constrained action hypothesis obtained within healthy adults generalizes to the stroke population, one may hypothesize that patients' and therapists' predominant reliance on using an internal focus actually impedes patients' automaticity of movement. As a result, this would not only impair their motor functioning, but possibly exacerbate dual-task interference as well. However, it is yet unclear whether the predictions of the constrained action hypothesis hold for stroke patients. In fact, results of the few studies that addressed the effects of attentional focus on single-task motor performance are ambiguous, with two studies reporting external focus[209,211] and one study reporting internal focus[289] to lead to superior upper extremity motor performance after stroke. The effects of attentional focus on patients' automaticity of movement are even less well understood. Results of Fasoli et al.[209] and Durham et al.[211] showed that the deceleration phase of reaching was significantly shorter in duration when attention was focused externally compared to internally. The authors argued that these findings do suggest a reduction in on-line guidance during moving, but did not explicitly relate these findings to enhanced automaticity of movement. Also, neither study assessed whether an external focus results in superior dual-task performance after stroke.

Hence, the current study aimed to assess whether the constrained action hypothesis holds true for stroke patients by examining the immediate effects of internal and external attentional focus on motor performance in people with chronic (> 1 year), unilateral stroke. Patients performed a single-leg stepping task in isolation and in combination with two different cognitive dual-tasks. This experimental paradigm was chosen because it has been validated in an earlier study into attentional focus effects and dual-task interference in healthy adults.[86] If the constrained action hypothesis holds true for stroke patients, then they would demonstrate superior single-task leg-stepping performance (i.e., greater movement speed) with an external focus instruction compared to an internal focus instruction. In addition, we hypothesized that an external focus would result in enhanced movement automaticity, which would be evidenced by greater fluency of movement. Because enhanced movement automaticity captures less working memory capacity, we also anticipated an external focus instruction to result in reduced dual-task interference compared to an internal focus instruction. Finally, we explored whether individual differences (i.e., patients' cognitive and motor capacities, and their inclination to use an internal focus in daily life) modified the (presumed differential) effects of attentional focus on single- and dual-task performance.

2. Methods

2.1. Participants

We recruited thirty-nine chronic stroke patients from three adult day care centers of Heliomare in the Netherlands between the 1st of May 2013 and the 1st of April 2014. Power analysis with G*power had shown that inclusion of at least 33 patients was necessary to be able to detect a small to moderate effect of focus on motor performance (based on repeated measures analysis of variance with an alpha-level of .05 and a power of .80). Inclusion criteria were as follows: 1) Unilateral, supratentatorial stroke confirmed by CT or MRI (obtained from patients' records); 2) Time since injury > 1 year; 3) Capable of understanding instructions (i.e., able to perform the three-step command-item of the mini mental-state examination[290]); 4) Between 18 and 75 years old. All participants provided written informed consent.

2.2. Ethics statement

The study protocol was approved by the medical-ethical committee of the VU Medical Center in Amsterdam (VUMC protocol ID: 2012/463).

2.3. Experimental tasks

2.3.1. Motor task

The motor task was a single-leg-stepping task (Figure 8.1). Participants alternately flexed and extended their leg at a self-selected, comfortable pace for 60 seconds while seated.[86] Both legs were tested. In external focus conditions, a line was taped to the floor such that when participants placed their foot on the line their knee was flexed at an angle of 90 degrees (Figure 8.1, left panel). In the internal focus conditions this line was removed. Motor performance was defined as movement speed – i.e., the average absolute angular velocity in the anterior-posterior plane. Increases in comfortable pace were considered to reflect superior motor performance (analogous to tasks like the 10 meter timed walk test[224,275]). This leg-stepping paradigm was chosen because it is a highly controlled task that is easy and safe to perform, and because it enables us to separately investigate the effects of different foci on (relatively more automated) non-paretic and (relatively less automated) paretic leg performance. Finally, we have previously validated this paradigm in an earlier study into attentional focus effects within healthy participants.[86]

Automaticity of leg-stepping performance was assessed by measuring the fluency of movement. The rationale is that as motor control becomes more automatic, movement fluency increases.[262,263] Movement fluency is typically operationalized as "jerk", a measure that is derived from the minimal jerk model[264] and defined as the rate of change of acceleration of the moving limb. Thus, less jerky/more fluent movement execution is considered to reflect more automatic motor control.

Figure 8.1. Motor task. In the external focus condition (left figure) patients were instructed to focus on placing their foot in front of/behind a line that was taped on the floor. In the internal focus condition (right figure) patients were instructed to focus on flexing and extending their leg. Figure adapted with permission from Kal et al.[86]

2.3.2. Cognitive tasks

Two different types of cognitive tasks were chosen: a letter fluency task (which is considered an executive function task) and an auditory reaction time task (taxing sustained attention). As reviewed by Al-Yahya et al.,[291] reaction time tasks generally yield less dual-task interference than executive function tasks. Incorporating these two types of cognitive tasks thus allowed us to compare the effects of attentional focus on dual-task performance as a function of task difficulty. In addition, incorporating a reaction time task also allowed us to include patients who might have difficulties with the letter fluency task as a consequence of aphasia.

The letter fluency task[272] required participants to name as many unique Dutch words as possible starting with a pre-specified letter within 1 minute. The outcome variable was the total number of words. Nine letters with a similar level of difficulty were chosen: D-A-T-K-O-M-P-G-R.

For the auditory reaction time task (ARTT), participants were presented with 18 auditory stimuli: 9 target stimuli (i.e., car horn) and 9 non-target stimuli (either the sound of a bell, a barking dog, or a whistle). Participants were required to react as fast as possible by saying "yes" whenever the target stimulus was presented, but had to ignore the non-target stimuli. Each stimulus was presented for 300 ms at 3-second intervals, with a time delay of -750 ms, -375 ms, 0 ms, +375 ms, or +750 ms to prevent anticipation. Order of stimuli and time delays were randomized. The dependent variable was reaction time in ms (for the correct responses).

2.3.3. Neuropsychological & motor assessments

General cognitive capacity was screened with the Dutch version of the MMSE.[290] Furthermore, specific tests for executive functioning, working memory, and attention were administered (see Table 8.1). Raw scores were corrected for patients' educational level and age by calculating Z-scores. For the executive function and attention domains, Z-scores of subtests were averaged, yielding one Z-score for each domain (see Table 8.1).

Motor capacity of the most-affected leg was assessed with the lower extremity subscales of the Fügl-Meyer Assessment[292] and Motricity index.[293]

Finally, to assess patients' preference to monitor and control their movements with an internal focus in daily life, patients filled out the Dutch version of the Movement-Specific Reinvestment Scale (MSRS).[29,181] This self-report scale includes 10 items. Five items form the subscale "Movement Self-Consciousness", and reflect the degree to which someone feels self-conscious about his/her style of movement (i.e., "I am concerned about what people think about me when I am moving"). The other 5 items belong to the "Conscious Motor Processing" subscale, and reflects one's inclination to consciously control movements in daily life ("I try to think about my movements when I carry them out"). Items are scored on a 6-point Likert scale ranging from 0 (strongly disagree) to 5 (strongly agree). Hence, scores range from 0-25 for each subscale, and between 0-50 for the whole scale. Higher reinvestment scores suggest a stronger preference to explicitly monitor (Movement Self-Consciousness) and control (Conscious Motor Processing) movements in daily life,[294] and hence, suggest a stronger preference to focus internally.

Table 8.1. Cognitive domains and associated neuropsychological tests.

Cognitive domain	Test	Alternative for aphasics	Outcome parameter
Executive Function	D-KEFS TMT -switching condition (divided attention)[295]	Color Trails Test -switching condition (divided attention)[229]	Time to complete (s)
	Tower of London (planning abilities)[296]	N/A	# moves needed to complete whole test
Working Memory	WAIS – letter/number sequencing[297]	WAIS - Symbol Span[298]	# correct sequences
Attention	D2-concentration test[230]	N/A	CP-score
	D-KEFS TMT - number sequencing condition[295]	Color Trails Test - number sequencing condition[229]	Time to complete (s)

NB: For aphasic patients, the Color Trails Test and WAIS Symbol Span were administered as alternatives for the D-KEFS and WAIS letter/number sequencing tests. CP-score = concentration performance score; TMT = trail making test; WAIS = Wechsler Adult Intelligence Scale; # = number of; N/A = not applicable;

2.3. Procedure

Measurements were performed on three occasions, separated by at least 24 hours. Pilot testing revealed the whole protocol to be too fatiguing and time-consuming to be completed within one measurement occasion.

On the first measurement day, the neuropsychological tests, the Dutch MSRS, and tests of motor capacity were administered. On the second measurement day, single-task performance on the letter fluency task and ARTT was assessed. Next, participants performed two blocks (first with one leg, then with the other) with the same attentional focus consisting of six 60-second trials: two single-task trials, two letter fluency dual-task trials, and two ARTT dual-task trials. For dual-task trials, patients were instructed to prioritize the motor task. Prior to the start of each trial, attentional focus was instructed. Internal focus instructions were to focus on "alternately flexing and extending the leg", whereas external focus instructions were to focus on "alternately placing the foot in front of and behind the line".[86] During trials, instructions were (briefly) repeated every 20 seconds to ensure compliance. Trials were separated by two minutes of rest. On the third measurement day, this procedure was repeated with the other focus. Also, single-task performance on the ARTT and letter fluency task was assessed again. The order of focus (i.e., external versus internal focus) was counterbalanced across participants. Participants always performed the two single-task trials first. The order of the motor-cognitive dual-task conditions (leg-stepping task + ARTT versus leg-stepping task + letter fluency) and legs (affected versus non-affected) was counterbalanced across participants. Figure 8.2 summarizes the experimental procedure.

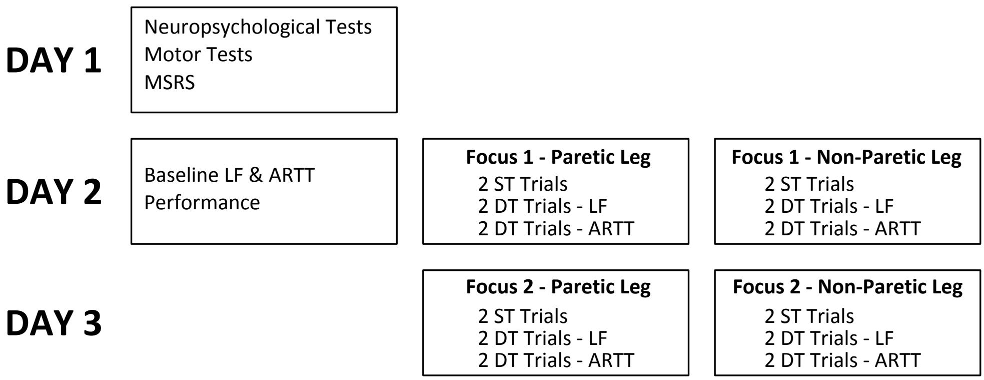


Figure 8.2. Measurement protocol. NB: ARTT = Auditory Reaction Time Task; ST = single-task; DT = dual-task;

2.4. Equipment and data collection

Seismic tri-axial hybrid accelerometers (DynaPort-MiniMod; McRoberts B.V., The Hague, The Netherlands) were used to measure the acceleration and angular velocity of the lower legs during the leg movement task. Accelerometers were attached to the tibia, approximately halfway an imaginary line from the lateral epicondyle to the lateral malleolus. The xyz-coordinate system of the accelerometer was defined such that the x-axis pointed forward (i.e., in the anterior-posterior plane), the y-axis pointed sideward (i.e., in the medio-lateral plane), and the z-axis pointed upward (i.e., in the transversal plane) when the knee was flexed 90 degrees. Data was stored at an internal SD card at 100 Hz.

Focus instructions and auditory stimuli were presented with customized software (Mixcraft 6; Acoustica Inc; CA; USA) via a headset. Number of words named (letter fluency task) and responses on the ARTT were recorded with a directional microphone, and sampled at 10000 Hz using customized LabVIEW software (National Instruments; Austin; Texas). All experimental trials were recorded with a video-camera with sound recording.

2.5. Data analysis

Accelerometer data and ARTT data were analysed with customized Matlab programs (Mathworks, Natick MA, USA). As each condition was measured twice (e.g., two single-task trials for each task, two letter fluency dual-task trials, two ARTT dual-task trials), average values were calculated for each condition.

To assess motor performance, the angular velocity in the mediolateral plane was filtered with a bidirectional, low-pass Butterworth filter (cut-off frequency: 5 Hz), rectified, and averaged over the whole 60 seconds of each trial, yielding the average movement speed per trial in degrees per second. Movement fluency was operationalized as the dimensionless jerk.[264] It is imperative to use the dimensionless jerk rather than the raw jerk, as raw jerk values are biased by differences in movement duration and amplitude.[264] Dimensionless jerk was determined as in our previous study.[86] For each flexion-extension movement cycle the resultant acceleration was calculated, and normalized (divided by its mean). Next, the derivative of the normalized resultant acceleration was obtained, yielding the mean rectified jerk. Then, to obtain a dimensionless measure, the mean rectified jerk values were multiplied with the duration of the flexion-extension cycle. Finally, calculating the mean of dimensionless jerk values across all movement cycles yielded the average dimensionless jerk for the whole trial.

Letter fluency performance was defined as the number of words per trial. Task performance was scored offline from video recordings by an independent neuropsychologist who was blind to the study goal. ARTT performance was assessed by determining the median difference (in ms) between target stimuli and associated responses for each trial. Dual-task performance was operationalized by calculating dual-task costs (DTCs[14]) for motor and cognitive tasks (see Equation 5.2). A positive DTC reflects a deterioration in performance in dual-task conditions.

2.6. Statistics

All statistical analyses were executed using SPSS version 20.0. The effects of attentional focus on single-task movement speed and movement fluency were analysed with two separate generalized estimating equation (GEE) analyses. GEE is a type of regression analysis that corrects for the dependency of repeated measurements. We chose an exchangeable working correlation matrix to define dependency amongst measurements. movement speed or movement fluency were the dependent variables, while focus (external vs. internal) and leg (paretic vs. non-paretic) were predictors.

Before comparing dual-task performance between conditions, we first checked whether significant dual-task interference occurred. Holm-Bonferroni[237] corrected paired-samples t-tests were conducted to test whether DTCs were significantly different from zero. Subsequently, the effect of attentional focus on dual-task costs was assessed with GEE, with

DTCs as the dependent variable, and focus (external vs. internal), leg (paretic vs. non-paretic), source (of DTCs; motor vs. cognitive) and type of dual-task (letter fluency vs. ARTT) as predictors. A similar GEE was then conducted with movement fluency as dependent variable to assess whether dual-task movement fluency differed as a function of focus, leg, and type of dual-task.

For all the above GEE analyses, significance of interactions between the main predictors (i.e., focus, leg, source, and type of dual-task) was assessed. The first, preliminary GEE model included all possible interactions. Using a backward approach, the (least contributing) interaction term was removed in turn, such that only near-significant ($p < 0.10$) interaction terms were retained in the final GEE model.

Finally, we explored whether the effect of focus on single- and dual-task performance was modified by cognitive capacity (executive function, working memory, or attention domain z-scores), motor capacity (Fügl-Meyer and Motricity Index), and/or patients' preferences for using an internal focus (reinvestment-scores). These variables were added to the single- and dual-task performance GEE-models in turn. Effect modifiers were identified if they significantly interacted with the predictor focus.

3. Results

All 39 patients completed the experiment (see Table 8.2 for characteristics). Worthy of note, 7 patients were incapable of performing the motor task with their paretic leg. Five other patients could not complete the letter fluency test, due to severe expressive aphasia. One patient showed extreme jerk scores (> 3 SDs above group mean) and was therefore excluded from the jerk analyses. In all, 27 patients performed the whole protocol (assessment of both legs in both motor-cognitive dual-task conditions), and 32 performed the whole protocol minus the letter fluency task.

3.1. Single-task results

3.1.1. Effect of focus of attention on single-task motor performance

Single-task motor performance results are depicted in Figure 8.3. GEE analysis (Table 8.3) revealed no significant differences in movement speed between internal and external focus conditions ($p = 0.341$), but higher speeds in non-paretic compared to paretic leg movements ($p < 0.001$). As no significant interaction was found between focus and leg ($p = 0.387$), this interaction term was left out of the final single-task GEE model (see Table 8.3).

Subsequent effect modification analyses revealed that the effect of focus on single-task performance was not modified by patients' cognitive capacity or Motricity Index scores (all: p's ≥ 0.2). However, patients' Fügl-Meyer scores (Wald $\chi^2 = 2.99$, $\beta = -0.38$, $p = 0.084$, 95% *CI* = [-0.81, 0.05]) and reinvestment scores (Wald χ^2 = 6.56, β = 0.40, *p* = 0.010, 95% *CI* = [0.09, 0.70]) did modify the effect of focus. That is, patients with higher Fügl-Meyer scores showed larger improvements in leg-stepping speed in external focus conditions (β = 2.32) than in internal focus conditions (β = 1.93). Also, patients with higher reinvestment scores showed larger reductions in leg-stepping speed in external focus conditions (β = -0.81) than in internal focus conditions (β = -0.41). Closer inspection of MSRS-subscale scores revealed this effect to be most pronounced for Movement Self-Consciousness scores (β = 0.49, *p* = 0.018), and less so for Conscious Motor Processing scores (β = 0.53, *p* = 0.15). Combined, these findings suggest that patients with more pronounced motor impairments and stronger reinvestment tendencies benefit more from internal focus instructions than from external focus instructions (and vice versa).

Table 8.2. Patient characteristics.

Group Characteristics	**Mean ± SD**
n	39
Age in years ± SD	62.62 ± 8.6
Female/Male	17/22
Lesion location: Left/Right	20/19
Lesion aetiology	
Haemorrhage	12
Infarction	27
Time since stroke (months)	113 ± 87
Aphasia: Yes/No	13/26
Cognitive Capacity	
Education level[a] (0-6)	4.15 ± 0.8
MMSE (0-30)	28 ± 2.2
Executive Function (Z-score)	-1.05 ± 1.1
Working Memory (Z-score)	-0.76 ± 0.9
Attention (Z-score)	-1.36 ± 0.9
Motor Capacity (of lower extremity)	
Fügl-Meyer (0-28)	19.3 ± 5.8
Motricity Index (%)	63.1 ± 18.7
Movement-Specific Reinvestment Scale (0-50)	31.8 ± 7.2
Movement Self-Consciousness (0-25)	13.7 ± 5.7
Conscious Motor Processing (0-25)	18.1 ± 3.5

[a] Education level is based on the international standard classification of education.[243]

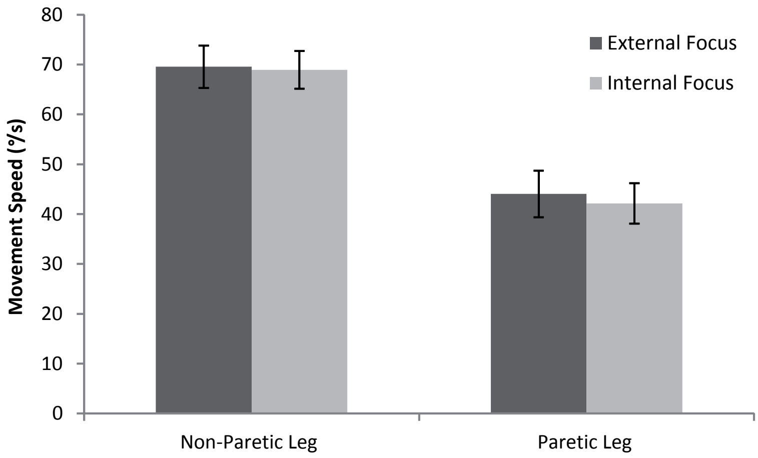


Figure 8.3. Single-task movement speed. Movement speed is expressed in degrees per second ± standard error.

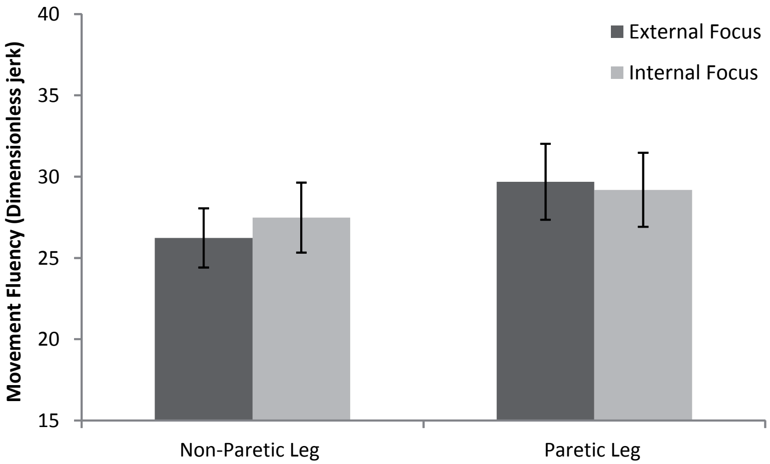


Figure 8.4. Single-task movement fluency. Movement fluency is expressed in dimensionless jerk ± standard error, with lower values indicating more fluent movement execution.

3.1.2. Effect of focus of attention on single-task movement fluency

Figure 8.4 shows results of movement fluency during single-task conditions, while Table 8.4 lists results of the corresponding GEE analysis. Movement fluency did not differ as a function of attentional focus ($p = 0.644$). Non-paretic leg movements were significantly more fluent than paretic leg movements ($p = 0.011$). However, the near-significant interaction between focus and leg ($p = 0.068$) indicated that this difference in fluency between legs was more pronounced in external focus conditions ($p = 0.062$) than in internal focus conditions ($p = 0.380$).

3.2. Dual-task results

3.2.1. Dual-task costs

At baseline, stroke patients on average listed 9.9 words (± 3.9) on the letter fluency task, and responded within 539 ms (± 163) on the target stimulus in the auditory reaction time task (ARTT). First, we assessed whether significant dual-task interference occurred when these tasks were simultaneously performed with the leg-stepping task (see Figure 8.5 for a summary of dual-task costs). To this end, we determined whether DTCs significantly differed from zero – i.e., single-task performance – using Holm-Bonferroni t-tests. Motor DTCs for the auditory reaction time task were significantly lower than zero for the non-paretic leg (*t's* (38) > 4.6, $p < 0.01$, $d > 1.5$) but not for the paretic leg (*t's* (31) < 1.1, $p > 0.3$, $d < 0.41$). This indicated that the non-paretic leg moved faster in ARTT dual-task conditions than in single-task conditions. For the letter fluency dual-task conditions, no significant motor DTCs were found (*t's*(26-33) ≤ 2.2, *p's* ≥ 0.17, *d's* ≤ 0.77), with the exception that significant negative DTCs were evident for the non-paretic leg in internal focus conditions ($t(33) = 2.9$, $p = 0.04$, $d = 1.0$). With regard to cognitive DTCs, significant positive DTCs were noted for both the ARTT and letter fluency dual-task conditions (*t's* (26-38) > 2.2, *p's* < 0.05, *d's* > 0.77; see Figure 8.5). In sum, although motor performance was not disrupted by dual-tasking, cognitive task performance deteriorated.

3.2.2. Effect of focus of attention on dual-task costs

Having established that significant dual-task interference occurred (especially for the cognitive tasks), we subsequently assessed whether DTCs differed as a function of focus, leg, source, and type of dual-task. The corresponding GEE-analysis revealed a trend towards significance for focus ($p = 0.065$), and significant effects for leg ($p < 0.001$), source ($p < 0.001$), and type of dual-task ($p = 0.040$), but no interaction effects (all *p*'s > 0.2; Table 8.3). The near-significant effect of focus was due to an internal focus generally leaning toward lower DTCs than an external focus. Also, significantly lower DTCs were noted for the non-paretic compared to the paretic leg conditions, for the motor compared to the cognitive task conditions, and for the ARTT compared to letter fluency task conditions.

Subsequent effect modification analyses revealed that focus did not significantly interact with motor capacity, executive function, working memory, or reinvestment scores (all *p*'s > 0.3). However, we did find a near-significant interaction between focus and attention domain scores (Wald $\chi^2 = 3.69$, $\beta = 2.36$, $p = 0.055$, 95% $CI = [-0.05, 4.76]$): Better attentional capacity tended to reduce dual-task costs in external focus conditions ($\beta = -2.98$) more than in internal focus conditions ($\beta = -0.62$).

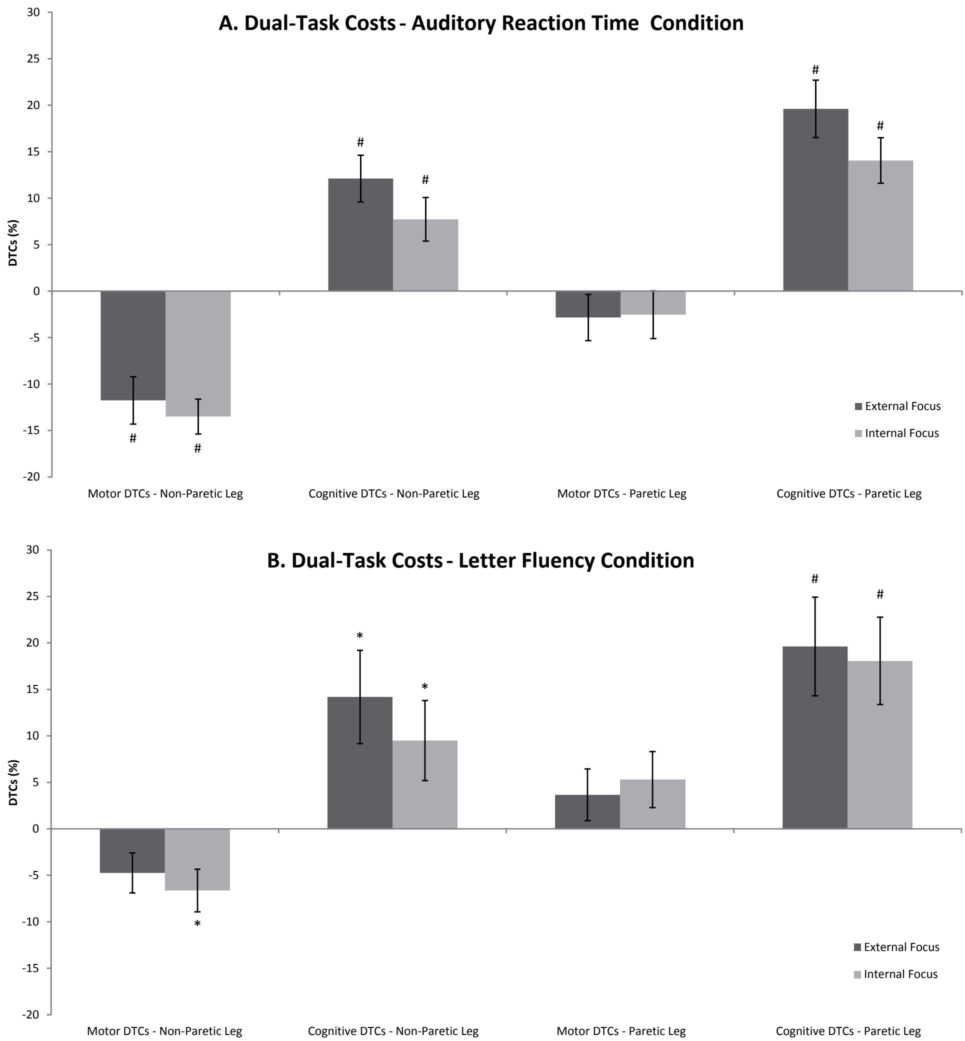


Figure 8.5. Average motor and cognitive dual-task costs. (A) Dual-task costs for the ARTT dual-task conditions. (B) Dual-task costs for the letter fluency dual-task conditions. Dual-task costs are expressed in percentages ± standard error. Positive dual-task costs indicate deteriorated performance compared to single-task conditions. Striped bars represent external focus conditions, solid bars indicate internal focus conditions. Dual-task costs that significantly differ from zero (i.e., single-task performance) are marked with an * ($p < 0.05$) or with an # ($p < 0.01$). NB: DTC = dual-task cost;

3.2.3. Effect of focus of attention on dual-task movement fluency

Figure 8.6 shows fluency of movement during dual-task conditions. Overall, movement fluency was similar in internal and external focus conditions (p = 0.132; Table 8.4), but greater for the non-paretic leg than for the paretic leg (p = 0.018). However, similar to the analysis of single-task movement fluency, a near-significant focus by leg interaction was found (p = 0.084). This suggested that movement fluency only differed between legs when attention was focused externally (p = 0.043) but not when attention was focused internally (p = 0.282). Finally, movement execution tended to be more fluent in ARTT dual-task conditions than in letter fluency dual-task conditions (p = 0.076).

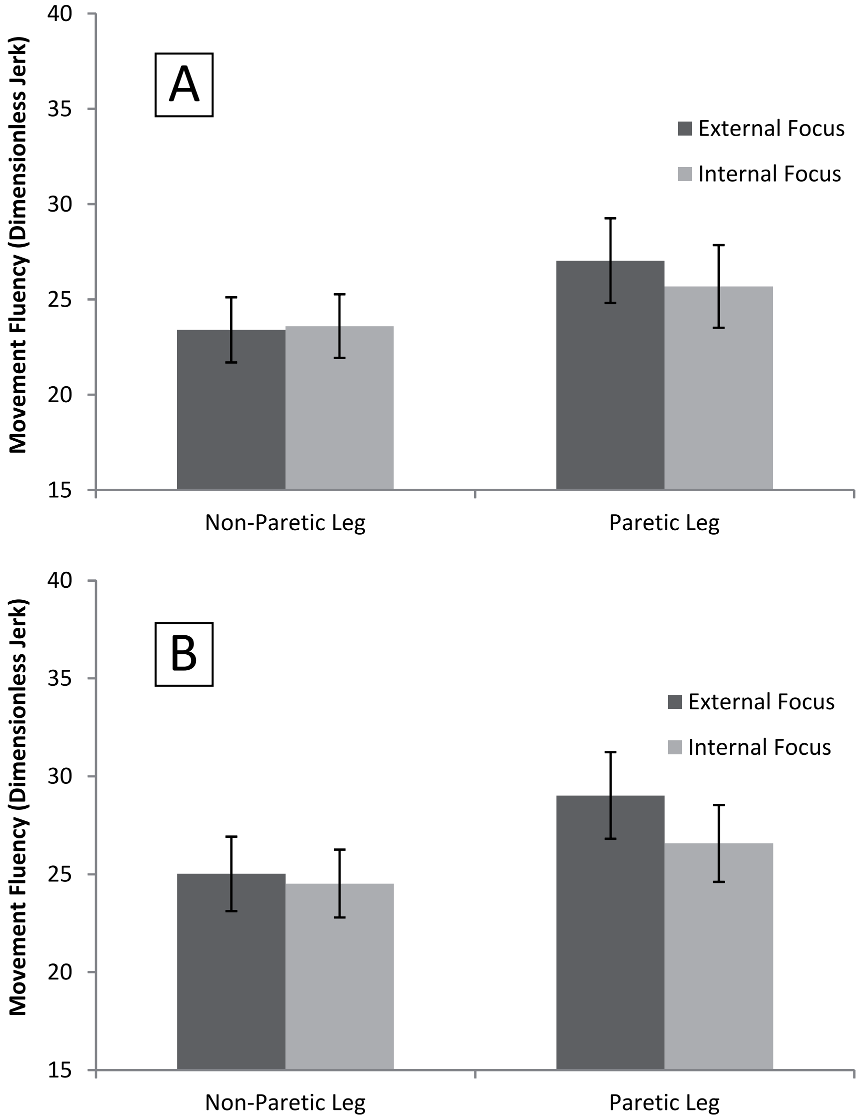


Figure 8.6. Dual-task movement fluency. (A) Movement fluency results for the ARTT dual-task conditions. (B) Movement fluency results for the letter fluency dual-task conditions. Movement fluency is expressed in dimensionless jerk ± standard error. Lower jerk values indicate greater movement fluency.

Table 8.3. Summary of results of GEE analyses of single- and dual-task performance.

	Wald χ^2	Beta	p	95% CI of Beta
Single Task Movement Speed				
Focus *(Internal vs. External)*	0.91	-1.92	.341	[-3.7, 0.9]
Leg *(Non-Paretic vs. Paretic)*	47.26	28.17	**<.001**	[20.1, 36.2]
Dual-Task Costs				
Focus *(Internal vs. External)*	3.40	-2.38	*.065*	[-4.9, 0.1]
Leg *(Non-Paretic vs. Paretic)*	69.35	-8.68	**<.001**	[-10.7, -6.6]
Source of DTCs *(Motor vs. Cognitive)*	65.60	-18.85	**<.001**	[-23.4, -14.3]
Type of Dual-Task *(ARTT vs. Letter Fluency)*	4.20	-4.50	**.040**	[-8.8, -0.2]

NB: Significant p-values are emphasized, while near-significant p-values are in italics.

Table 8.4. Summary of results of GEE analyses of movement fluency.

	Wald χ^2	Beta	p	95% CI of Beta
Single Task Movement Fluency				
Focus *(Internal vs. External)*	.214	-.49	.644	[-2.6, 1.6]
Leg *(Non-Paretic vs. Paretic)*	6.52	-3.65	**.011**	[-6.4, -.8]
Focus x Leg Interaction[a]	3.33		*.068*	
Internal Focus x Paretic Leg	4.52	3.16	**.034**	[0.2, 6.1]
Internal Focus x Non-Paretic Leg	2.52	1.26	.112	[-0.3, 2.8]
External Focus x Paretic Leg	6.52	3.65	**.011**	[0.8, 6.4]
Dual-Task Movement Fluency				
Focus *(Internal vs. External)*	2.27	-.99	.132	[-2.3, 0.3]
Leg *(Non-Paretic vs. Paretic)*	5.58	-3.04	**.018**	[-5.6, -.5]
Type of Dual-Task *(ARTT vs. Letter Fluency)*	3.14	-1.34	*.076*	[-2.8, 0.1]
Focus x Leg Interaction[a]	2.99		.084	
Internal Focus x Paretic Leg	2.30	2.05	.130	[-0.6, 4.7]
Internal Focus x Non-Paretic Leg	.07	-0.13	.795	[-1.1, 0.8]
External Focus x Paretic Leg	7.20	3.90	**.007**	[1.1, 6.7]

NB: Significant *p*-values are emphasized, while near-significant *p*-values are in italics. [a]= for the interaction terms, External Focus x Non-Paretic Leg served as reference.

4. Discussion

This study set out to test the constrained action hypothesis within chronic stroke patients. Specifically, we examined the prediction that – compared to an internal focus – an external focus acutely enhances chronic stroke patients' motor performance by promoting more automatic motor control. To this end, we compared the effect of external and internal focus instructions on patients' leg stepping speed, as well as on a kinematic proxy of automaticity:

fluency of movement. Finally, as more automatic movements should place a lower demand on working memory resources, we also assessed whether external focus instructions enhanced dual-task performance compared to internally referenced instructions.

4.1. Effect of focus on motor performance, automaticity of movement, and dual-task performance of stroke patients

Single-task movement speed remained stable in the face of different attentional focus instructions, regardless which leg was used. This sharply contrasts the numerous studies that have found an external focus to lead to superior motor performance in healthy adults [6-8]. The present results are especially at odds with those of our previous study in which we used an identical leg-stepping paradigm, and found that healthy adults demonstrate superior single-task leg-stepping speed with external focus instructions compared to internal focus instructions.[86] Our present results thus add to the heterogeneity of earlier findings regarding the effects of attentional focus on motor behavior after stroke.[209,211,289] At the very least, this suggests that for chronic stroke patients as a group, an external focus does not acutely benefit single-task motor performance compared to an internal one.

The analyses of fluency of movement and dual-task performance may provide clues as to why the motor performance benefits obtained within healthy adults do not seem to uniformly generalize to the stroke population. Congruent with the single-task movement speed results – but contrary to hypothesized – an external focus did not result in greater movement fluency than an internal focus, neither in single- nor in dual-task conditions. Focus by leg interactions suggested a reverse pattern, with an external focus reducing movement fluency of the paretic leg. These findings seem in line with the analysis of dual-task performance, which also failed to show a benefit of an external focus of attention. Rather, DTCs tended to be higher when patients focused externally, and patients' attentional capacity tended to constrain dual-task performance in external but not internal focus conditions. Combined, these findings tentatively suggest that an external focus was more reliant on attentional functioning (and hence: less automatic) than an internal focus. Again, as for the single-task results, these findings sharply contrast those of our previous study, in which healthy adults showed superior movement fluency and dual-task performance with external focus instructions.[86]

In sum, the constrained action hypothesis' predictions were not confirmed within a group of chronic stroke patients: Compared to an internal focus, an external focus of attention did not acutely benefit motor performance, enhance fluency of movement, or reduce dual-task interference. Weak but consistent findings of reduced automaticity with an external focus might imply that external focus instructions can have a negative effect on automaticity of movement and dual-task performance of stroke patients.

4.2. Effect of attentional focus on automaticity – modulating role of focus familiarity and attentional capacity

What could possibly explain the unexpected lack of enhanced – and trends toward reduced – automaticity with an external focus? A possible explanation stems from Maurer and Munzert,[215] who showed that the effect of the *direction* of attentional focus (i.e., internal vs. external) on motor performance can be confounded by the performer's preference for either type of focus (see also[299]). In two experiments, healthy adults performed best (on a golf-putting and on a basketball free throw task) when they were instructed to use the attentional focus they were most familiar with, regardless whether this constituted an external or internal focus. To explain these findings, the authors proposed that 'Frequently used attentional strategies may become integrated parts of the skill and no longer impact on automated skill execution' (p. 737). By contrast, adopting a non-familiar focus is highly attention-demanding, and hence disrupts automated motor performance. A similar phenomenon may in part explain the results of our study. The high reinvestment scores of our patient group (Table 8.2) suggest that the majority of patients was prone to habitually adopt an internal focus of attention. Building on Maurer and Munzert's results, we hypothesize that focusing internally may thus have been a more familiar, less attention-demanding strategy for these patients than adopting an external focus. This hypothesis is in line with the finding that for patients with high reinvestment scores single-task leg-stepping speed was enhanced by internal rather than external focus instructions. Furthermore, this hypothesis would explain why adopting an external focus especially reduced fluency of paretic leg movements (especially if one assumes that patients are most inclined to focus internally when moving their most-affected leg), why attentional capacity seemed more important for dual-task performance under an external focus of attention, and hence, why patients performed worst at dual-tasking in external focus conditions.

Admittedly, the hypothesized role of preferred focus would be more strongly supported if patients' reinvestment scores had also directly modulated the effect of attentional focus on dual-task performance. The fact that they did not might partly be due to the fact that reinvestment scores clustered at the top end of the scale range, with 75% of patients scoring 25 points or higher. Future research may explicitly address the presumed role of focus preference in stroke patients and healthy adults in more detail. Possibly, these studies may also use measures that more directly assess (the strength of) individual focus preferences, for instance by having performers rate the mental effort required to adhere to different focus instructions.[215]

4.3. Dual-task performance – effects of legs, type of dual-task, and task prioritization

A final note concerns the difference in dual-task performance that emerged as a function of leg, type of dual-task condition, and source of costs (motor vs. cognitive). The fact that the ARTT yielded less dual-task interference than the letter fluency task fits the results of a recent meta-analysis.[291] The observation that dual-tasking primarily affected cognitive task performance indicates that patients complied with the instruction to prioritize motor performance. The differences between the paretic and non-paretic leg are of more interest, though. As expected, clear-cut differences were evident between legs in terms of dual-task performance; patients were more proficient at dual-tasking with their non-paretic leg than with their paretic leg. In the apparently easiest (ARTT) condition, non-paretic leg movement speed even increased compared to single-task conditions. These findings are in agreement with reports that distracting attention away from movement execution can benefit motor performance, as long as the motor skill is sufficiently automated and the secondary task is relatively easy.[300,301] Taken together, it seems that stroke patients may invest a superfluous amount of attention into their (otherwise relatively automated) non-paretic leg movements, even to the extent that it constrained their single-task performance. Patients' strategy to consciously control their movements – although likely intended to deal with the motor impairments of their paretic leg – thus also seemed to affect motor control of their non-paretic leg.

4.4. Limitations and implications for future research

The present study yields new insights and triggers new questions regarding the effects of attentional focus on (automaticity of) motor performance post-stroke. Its immediate implications for clinical practice are limited, though, for several reasons. For one, this study addressed acute performance effects, not motor learning (i.e., the long term retention of (re-) acquired motor skills).

Second – although it allowed us to investigate the effects of focus for both legs separately – the experimental leg-stepping task seems of limited functional relevance. It remains to be seen whether the results obtained with this highly controlled, relatively simple task generalize to more complex, clinically relevant motor tasks like walking. Still, the validity of this motor task seems supported by the fact that both Fügl-Meyer and Motricity Index scores significantly predicted performance on this task ($\beta_{FM} = 2.32$, $\beta_{MI} = 0.058$; both p's < 0.01).

Third, the stroke group in the present study mostly consisted of stroke patients who had suffered brain damage a relatively long time ago (almost 10 years on average), and who have all been involved in rehabilitative physical therapy in which they likely received a lot of internally referenced instructions and feedback.[43,178] For greater clinical relevance, future studies should compare the long-term effects of different attentional foci on re-acquiring and re-automating clinically meaningful motor skills (e.g., gait or postural control) already in the clinical/inpatient phase of stroke.

Furthermore, it is not unlikely that differences between different foci of attention average out on a group level, due to the large heterogeneity in cognitive and motor functioning within the stroke population. Therefore, an important venue for future research is to more specifically explore the modulatory role of individual patient characteristics. In this regard, the present study suggests that patients' motor capacity, focus preferences, and attentional capacity may be of interest. Further exploration of these issues is required in order to establish whether (and for whom) attentional focus instructions can be used to facilitate motor learning after stroke.

Finally, a general limitation of studies into the effect of attentional focus instructions on motor performance is that one can never be absolutely certain that participants complied with instructions. In this experiment, we tried to maximize compliance in several ways. First, before the start of the internal/external focus block patients were asked to repeat the instructed focus. Second, during each trial, instructions were briefly repeated at 20 and 40 seconds. Third, the instructions used in this study have been found to reliably induce external and internal foci of attention in our earlier study.[86] The fact that patients complied with the instruction to prioritize motor performance over cognitive task performance further strengthens our confidence that they also complied with attentional focus instructions.

5. Conclusion

In conclusion, the present study's results did not confirm the constrained action hypothesis' predictions within a chronic stroke population. Relative to an internal focus, an external focus did not directly enhance patients' motor performance, fluency of movement, or dual-task performance. Although effects were weak, it might be that an internal focus facilitates automatic motor control after stroke, possibly due to patients' pronounced inclination to consciously control their movements in daily life.

6. Acknowledgements

We would like to thank the personnel in the day care centres for their practical assistance during the measurements.

Chapter 9

Are the effects of internal focus instructions different from external focus instructions given during balance training in stroke patients?

A double-blind randomised controlled trial

Elmar Kal
Han Houdijk
John van der Kamp
Manon Verhoef
Rens Prosée
Erny Groet
Marinus Winters
Coen van Bennekom
Erik Scherder

Clinical Rehabilitation. 2018;(early online):1-15.

Abstract

Background: This double-blind randomised controlled trial aimed to assess if external focus instructions result in greater improvements in motor skill and automaticity compared to internal focus instructions in stroke patients.

Methods: We included sixty-three stroke patients in an inpatient stroke rehabilitation unit ($Mean_{age}$ = 59.6±10.7 years; $Mean_{days\ since\ stroke}$ = 28.5±16.6; $Median_{Functional\ Ambulation\ Categories}$ = 4). Patients were randomly assigned to an internal (N=31) or external (N=32) focus instruction group. Both groups practiced a balance board stabilization task, three times per week, for three weeks. Balance performance was assessed at baseline, and after one and three weeks of practice. Primary outcome was the threshold stiffness (Nm/radian) at which patients could stay balanced. Secondary outcomes were patient's sway (root-mean-square error in degrees) at the baseline threshold stiffness under single- and dual-task conditions, and their performance on the Timed-up-and-Go and Utrecht Scale for Evaluation of Rehabilitation.

Results: Both groups achieved similar improvements in threshold stiffness (Δ=27.1±21.1 Nm/radian), and single- (Δ=1.8±2.3° root-mean-square error) and dual-task sway (Δ=1.7±2.1° root-mean-square error) after three weeks of practice. No differences were found in improvements in clinical tests of balance and mobility. Patients with comparatively good balance and sensory function, and low attention capacity showed greatest improvements with external focus instructions.

Conclusions: External focus instructions did not result in greater improvement in balance skill in stroke patients compared to internal focus instructions. Results suggest that tailoring instructions to the individual stroke patient may result in optimal improvements in motor skill.

1. Introduction

Reacquiring motor skills is a challenging and protracted process for patients after stroke. Many patients suffer from cognitive and language deficits.[27,133,241] It is therefore pertinent that a therapist uses instructions that are concise, easy to process, but still sufficiently meaningful to help the patient improve motor performance. Recent studies in healthy adults suggest that this may be best achieved with instructions that direct attention 'externally', toward the desired movement outcome. External focus instructions are presumably less cognitively demanding than 'internal' focus instructions, which direct attention toward movement execution itself. Consequently, external focus instructions have been found to result in superior[57,99,208,256,258,302] and more automatic[56,86,87] motor skill in healthy adults and elderly.

Physical therapists increasingly use external focus strategies when treating stroke patients.[206] However, it is unknown if external focus instructions are effective for enhancing motor skill acquisition in this patient population. To date, the few studies available have solely investigated the *immediate* effects of attentional focus on motor performance, and with mixed results.[209–212] Only one randomised controlled trial has studied the effects of a 4-week intervention on arm function in chronic stroke patients, but it did not find any differences between groups.[213]

Individual patient characteristics may be important to consider when deciding on how to instruct patients. This is particularly true for therapists working in rehabilitation, given the large heterogeneity in the clinical presentation of stroke. This is supported by studies suggesting that external focus instructions could be especially effective for patients with good motor and sensory functioning, poor cognitive capacities, and weak conscious control preferences.[206,211,212]

Our aim was to conduct a double-blind randomised controlled trial to assess if external focus instructions result in greater improvements in motor skill and automaticity compared to internal focus instructions in patients after stroke. We hypothesized that patients who practice with external focus instructions would achieve greater improvements in motor skill and automaticity compared to patients who practice with internal focus instructions.

In addition, we explored whether specific patient characteristics influenced the relative efficacy of internal and external instructions. We hypothesized that external instructions would be more efficacious compared to internal instructions for patients with high motor and sensory functioning, low cognitive capacity, and weak conscious control inclination.

2. Methods

2.1. Protocol registration

The study protocol of this double-blind randomised controlled trial was approved by the medical ethical committee of the VU Medical Center in Amsterdam (ID: 2015.354) and pre-registered in the Dutch CCMO-register (NL54560.029.15).

2.2. Setting, participant recruitment and selection

Patients with stroke who were receiving inpatient care in rehabilitation centre Heliomare in Wijk aan Zee, The Netherlands were recruited between March 2016 and February 2017. At admission, the rehabilitation physician informed possibly eligible stroke patients about the study in writing and verbally, and invited them to participate. Patients were deemed possibly eligible if they had some degree of walking ability, and seemed able to follow instructions. More specifically, patients were recruited if they suffered a first-ever or recurrent stroke <6 months ago, had a Functional Ambulation Categories score >2, were able to stand independently >1 minute, were able to understand instructions and cooperate with neuropsychological assessment, had no other central nervous system or orthopedic impairments, and had no uncorrected visual or hearing impairment. Patients who were not able to follow instructions, or were not functionally ambulant (Functional Ambulation Categories score ≤ 2) at admission, were monitored throughout their stay. When they achieved Functional Ambulation Categories scores >2, their eligibility was further assessed. All patients provided written informed consent prior to inclusion.

2.3. Materials and measures

After inclusion, the following demographic information was collected: General characteristics (age, sex, body weight and height), stroke characteristics (recurrent stroke (yes/no), days since stroke and since admission to rehabilitation centre, stroke aetiology and subtype),[157] general functioning (Utrecht Scale for Evaluation of Rehabilitation),[233] co-morbidities using the Charlson Cormorbidity Index,[234] motor functioning (Functional Ambulation Categories,[235]Berg Balance Scale,[232] Ten Meter Walk-Test;[224] Timed-up-and-Go),[219] cognition (education,[303] attention (D2-attention test),[230] working memory (Digit-Symbol Substitution Test),[304] executive functioning (Color-Trails),[229] presence of aphasia/neglect), sensory functioning (Revised Nottingham Sensory Assessment – lower extremities),[231] the degree to which patients use conscious control of movement in daily life (Movement-Specific Reinvestment Scale),[134] and additional hours per week of physical-, occupational-, and sports-therapy received during the intervention period.

A custom-made, validated balance board task[305] was used to test patients' balance performance, and also for the interventions (Figure 9.1). This balance board task taxes mediolateral balance control, which is often impaired after stroke.[306–308] Patients' goal is to stand as still as possible on the balance board, for 30 seconds and without touching the handrail surrounding the board. Task difficulty can be manipulated by adjustment of the board's rotational stiffness (0-220 Nm/rad). All patients wore a harness to ensure their safety.

We used a modified staircase procedure[309,310] to determine the threshold stiffness (Nm/rad) at which patients were just able to maintain balance – i.e., keep board deviations below 2.5° for 70% of the trial. With this procedure, task difficulty is adjusted on a trial-to-trial basis, based on pre-specified criteria. Please see Brouwer et al. for the full test protocol.[305] Patients only received unfocused instructions ("stand as still as possible"). Lower threshold stiffness values indicate better balance performance. The rotational stiffness assessment has excellent test-retest reliability (ICC=0.87) and construct validity (r=-0.56 with Berg Balance Scale), and a minimum detectable change of 3.20 Nm/rad on group level.[305]

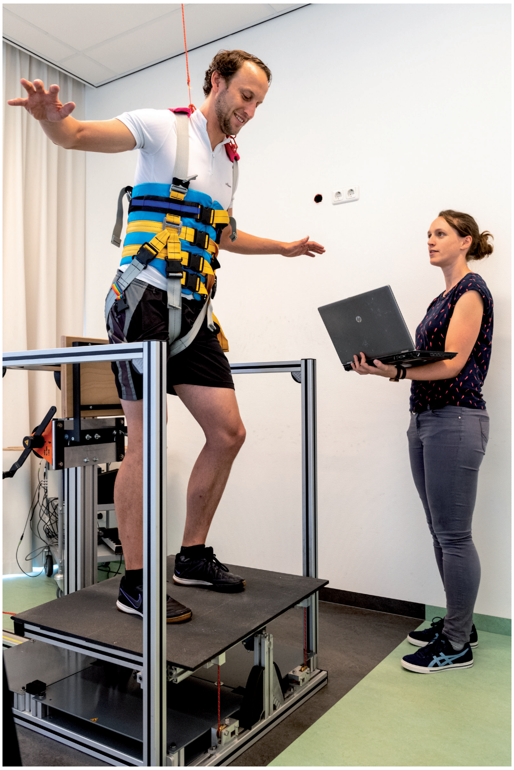


Figure 9.1. Balance board set-up. Springs were attached to each side of the front of the balance board. Rotational stiffness could be adjusted (0-220 Nm/rad) by using either one or two parallel springs on each side, by altering the springs' moment arm, or by changing the springs themselves (800 N/m vs. 390 N/m). Patients wore a safety harness.

Next, we measured patients' sway at their baseline threshold stiffness in single-task (as performance measure) and dual-task conditions (as automaticity measure). Sway was defined as the root-mean-square error deviation around the board's average position (degrees). Lower values indicate less sway and, hence, better performance. Patients performed 2 single- and 2 dual-task trials, in the following order: single-task—dual-task—dual-task—single-task. The dual-task was a tone-counting task.[50,56] Low (400 Hz) and high (1000 Hz) tones were presented randomly at 1.5-second intervals in a 1:2 ratio. Patients had to respond as quickly and accurately as possible by saying "yes" whenever a high tone was played, and reported the number of high tones after each 30-s trial.[212] Patients performed two single-task tone-counting trials to determine baseline single-task performance. After the balance board measurements, patients' movement-related knowledge was assessed. They verbally described all rules and strategies they had used to perform the balance task. This assessment serves as an extra check to determine the degree to which patients' balance performance relied on conscious motor control; a larger number of rules indicates greater reliance on conscious control.[47,56]

To evaluate the clinically relevant benefits of the interventions, we additionally assessed patients' scores on the Timed-up-and-Go [219]in single- and dual-task (tone-counting) conditions and on the Utrecht Scale for Evaluation of Rehabilitation-mobility subscale.[233]

2.4. Randomization and blinding

Baseline measurements were performed before randomisation took place. Hence, baseline assessors were blinded to group allocation. Patients were randomly allocated to the external or internal group by an independent researcher (MW) at a remote site who was blinded to the patient at randomisation, except for the variables for which stratification was performed. The researcher was otherwise not involved in the trial, nor in patient care. The primary investigator (EK) notified the independent researcher when a new patient had completed the baseline assessment. The independent researcher then used random number generator software (https://www.random.org) to block-randomise patients to the internal or external group (blocks of 4, allocation ratio 1:1; both only known to the independent researcher). Patients were stratified according to lesion location (sub- vs. supratentatorial) and baseline threshold stiffness (>60 vs. <60 Nm/rad). Group allocation was shared with the investigator (EK) who provided the intervention but not with the patient or outcome assessors (MV, RP), to minimize the risk of performance, detection and attrition bias.

2.5. Interventions

Patients in both groups practiced the balance board task for three weeks, three times per week, with 15 single-task trials per session. In the first practice session, the baseline threshold stiffness was used in the first block of five trials. Depending on patients' average performance (Table 9.1), stiffness was either increased (+20% Nm/rad), maintained, or decreased (-20% Nm/rad) in the next block, to ensure that task difficulty remained challenging throughout practice. Before each trial, the external focus group was instructed to "focus on the board, and keep the board as still as possible", while the internal group was instructed to "focus on your feet, and keep your feet as still as possible".[87,208]

Table 9.1. Criteria for evaluating success during practice sessions.

Performance criteria for practice sessions		
Average % of trial duration that board deviates < 2.5 degrees	*Number of trials participant grabbed handrail for support*	*Stiffness for next block of 5 trials*
>70%	1 or 2 trials	Stiffness-20%
>70%	>2 trials	No change
60%-70%	1 or 2 trials	No change
60%-70%	>2 trials	Stiffness+20%
<60%	Any number	Stiffness+20%an

NB: Handrail support was scored by observation by the experimenter.

After each session, we checked adherence. Patients rated (1) the effort needed to focus as instructed, (2) the effort needed to maintain the instructed focus throughout the trial, and (3) the effectiveness of the instructed focus, by putting a cross on a horizontal l0cm-line (0 cm="very little/effective"; 10 cm="very much/completely ineffective").[240] Scores below 5.0 cm indicate that patients were able to adhere to instructions, and found these to be more helpful than harmful for their performance.

2.6. Outcome assessments

Blinded assessors (MV, RP) performed outcome assessments after one and three weeks of practice. Both followed an identical procedure as the baseline assessment, except that the Timed-up-and-Go and Utrecht Scale for Evaluation of Rehabilitation were re-assessed after 3 weeks only. Patients were explicitly instructed not to tell which instructions they had received during practice.

The primary outcome measure was patients' individual threshold rotational stiffness. Secondary outcome measures were patients' sway at their baseline threshold stiffness in single-task and dual-task conditions, and their scores on the Timed-up-and-Go and Utrecht Scale for Evaluation of Rehabilitation.

2.7. Data processing

Potentiometer data and verbal responses on the tone-counting task were sampled at 1000 Hz using LabVIEW (National Instruments; Austin; Texas), and analysed with Matlab (Mathworks, Natick MA, USA). The balance board's potentiometer data was filtered with a bidirectional, low-pass (8Hz) Butterworth filter. We used non-linear regression to determine the patients' individual threshold stiffness (see Brouwer et al. for details).[305] To determine single- and dual-task sway, we calculated the root-mean-square error of board deviations (in degrees) per trial. For the tone-counting task, we calculated reaction time (ms), and response and counting accuracy (%) per trial. These were collapsed in a composite score (see equation 5.1).[236] Tone-counting dual-task performance was operationalized by calculating dual-task costs (DTCs; see equation 5.2).[14] Positive DTC indicates performance deterioration in dual-task versus single-task conditions.

Patient's self-reported verbal rules were transcribed verbatim and scored offline (EK) – only movement-related rules were scored. If conditions were measured twice (sway, tone-counting), values were averaged.

2.8. Sample size calculations & Statistics

Power analysis (G*power) showed a sample size of 52 to be sufficient to detect a small-to-moderate effect (f=.20), based on a repeated measures ANOVA (within-between interaction), alpha of .05, beta of .80, 2 groups, and r of 0.5. Expecting a drop-out of 10-15%, 60 patients (30/group) were needed.

All data were analysed with SPSS version 20.0. Patient characteristics were described with their appropriate central estimate and measures of dispersion, and were compared between groups to check whether randomization was successful.

Generalized Estimating Equations (GEEs) were used to compare learning effectiveness between groups. We used an autoregressive correlation matrix to define this dependency. First, we used GEE to model the association between the primary outcome, threshold stiffness, and the predictors group (external vs. internal), time (Baseline, 1 week, 3 weeks), and their interaction. Learning differences were considered present in case of significant group by time interaction. Similar GEEs were used for the analysis of the secondary outcomes, single- and dual-task sway. We a-priori decided to add the covariate "handrail support" to both sway analyses, as this factor likely influences sway. Similarly, tone-counting dual-task costs served as covariate in the dual-task sway analysis, to correct for any task-prioritization differences. Finally, we conducted GEEs (predictors group, time(baseline – 3 weeks follow-up), interaction) on Utrecht Scale for Evaluation of Rehabilitation–mobility subscale and single- and dual-task Timed-up-and-Go. Again, tone-counting dual-task costs were added to the dual-task analysis. For all GEE-analyses, Holm-Bonferroni t-tests followed up significant effects.[237] For these post-hoc t-tests, we presented the adjusted mean differences between groups or test sessions. Cohen's d served as measure of effect size.

We performed per-protocol analyses, and additional intention-to-treat analyses to determine whether attrition influenced results. For intention-to-treat, missing cases were imputed based on the overall median improvement in the respective outcome measures.[311] We assumed that drop-outs would show similar improvements as the other patients. Therefore, we estimated the median percentage improvement per outcome measure, and used these to estimate patients' performance on the missing test sessions.

We a-priori decided to investigate whether cognition (Color-Trails, Digit-Symbol Substitution Test, D2-attention test), motor capacity (Berg Balance Scale), conscious control inclination (Movement-Specific Reinvestment Scale), and sensory functioning (Revised Nottingham Sensory Assessment – lower extremities) had a different effect on learning in the external group than in the internal group. Variables were submitted to the respective GEE-models of stiffness, single- and dual-task sway in turn. Variables were labeled 'effect modifiers' when the group x time x '*variable*' term was significant. To assess how an effect modifier influenced learning per group, separate linear regression analyses were run with absolute learning improvements (3 weeks – Baseline) as dependent variable. Effect modification analyses were restricted to per-protocol analyses of the full three-week learning period.

3. Results

Sixty-three patients were included. Figure 9.2 shows the flow of the study. A total of 51 patients completed the whole intervention and assessment after 3 weeks.

Table 9.2 lists baseline characteristics of all included patients. There were no apparent baseline group differences, except that the external group seemed to be heavier than the internal group. Weight was positively associated with threshold stiffness at all three test sessions (B's≥0.523, p's≤0.011). Therefore, it was included as covariate in the analysis of threshold stiffness. Both groups indicated that they focused their attention as instructed during practice, confirming that they adhered to the assigned intervention. Please see Appendix 9.1 for more details.

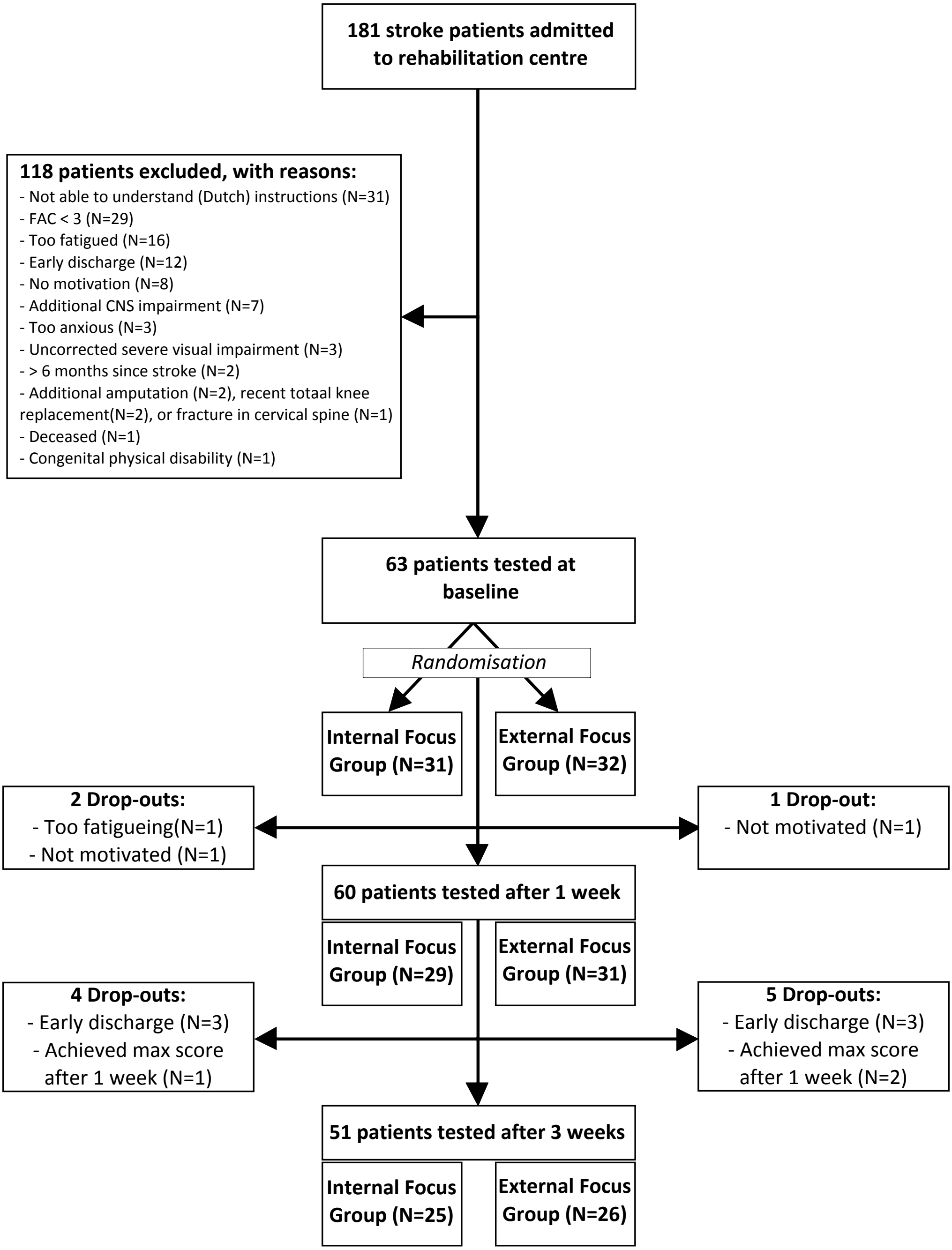


Figure 9.2. Study flow. Abbreviations: CNS=Central nervous system; FAC=Functional Ambulation Categories;

Table 9.2. Baseline characteristics per group.

Variable	Internal Focus Group (N=31)	External Focus Group (N=32)
General characteristics		
Age in years (mean±SD)	58.5±10.3	60.7±11.1
Sex (male/female)	23/8	20/12
Weight in kg (mean±SD)	77.6±12.1	83.7±16.1
Height in cm (mean±SD)	176.8±8.7	176.0±9.0
Leg length in cm (mean±SD)[c]	102.9±6.5	103.5±5.8
Stroke characteristics		
Days since stroke at baseline[a] (mean±SD)	30.5±21.3	26.6±10.3
Days since admission at baseline (mean±SD)	14.3±10.9	11.7±8.4
Stroke aetiology (haemorrhagic/infarction)	7/24	8/24
Stroke subtype		
Total Anterior Circulation Stroke	2	1
Partial Anterior Circulation Stroke	15	15
Lacunar Stroke	8	9
Posterior Circulation Stroke	6	7
Recurrent Stroke (yes/no)	3/28	4/28
Revised Nottingham Sensory Assessment – lower extremities (0-80; mean±SD)[a]	71.7±10.5	74.8±5.2
Charlson Comorbidity Index (mean±SD)[a]	0.52±0.6	0.78±1.2
Additional hours of therapy/week (mean±SD)[a]	8.1±2.3	8.3±1.7
Motor characteristics		
Berg Balance Scale (0-56; mean±SD)[a,b]	46.3±10.1	49.0±7.3
Functional Ambulation Categories (0-5; median±IQR)	4±2	4±1
Ten Meter Walk Test (s; mean±SD)[a]	17.1±9.9	14.1±8.6
Timed-up-and-Go -ST (s; mean±SD)[a]	19.5±11.1	16.6±11.3
Timed-up-and-Go -DT (s; mean±SD)[a]	21.1±11.7	18.0±11.8
USER-MOB (0-35; mean+SD)[b]	23.3±6.7	24.4±7.0
Cognitive characteristics		
Education level (1-7; median±IQR)	5±2	5±2
USER-COG (0-50; mean+SD)[a,b]	43.5±4.5	44.5±5.7
Aphasia (yes/no)	7/24	3/29
Neglect (yes/no)	9/22	6/26
Attention (D2-attention test; mean±SD)[d]	118.6±48.4	120.6±41.4
Working Memory (DSST; mean±SD)[c]	43.5±16.9	47.1±18.3
Executive Function (Color Trails Test; mean±SD)[e]	0.91±0.56	0.97±0.47
Conscious motor control preference		
MSRS-Total (mean±SD)	37.7±10.5	34.0±11.0
MSRS-CMP (mean±SD)	22.6±6.2	20.3±6.1
MSRS-MS-C (mean±SD)	15.2±5.4	13.7±5.9

NB: [a] Variable was not normally distributed, therefore a Mann-Whitney U test was performed; [b] Data unavailable for 1 patient; [c] Data unavailable for 4 patients; [d] Data unavailable for 5 patients; [e] Data unavailable for 7 patients. Abbreviations: CMP=Conscious Motor Processing subscale; COG=Cognitive subscale; CTT=Color Trails Test; DSST=Digit Symbol Substitution Test; IQR=Interquartile range; MOB=Mobility subscale; MS-C=Movement Self-Consciousness subscale; MSRS=Movement-Specific Reinvestment Scale; s=seconds; SD=Standard deviation; SE=Standard error; USER=Utrecht Scale for Evaluation of Rehabilitation;

3.1. Primary outcome

Table 9.3A summarizes threshold rotational stiffness per measurement session. Appendix 9.2 shows the development of rotational stiffness throughout practice. After three weeks of practice, the external group had improved by 25.8±18.6 Nm/rad, while the internal group had improved by 28.4±23.2 Nm/rad (main effect of time, $p<0.001$; Table 9.4A). However, this improvement in rotational stiffness did not differ between groups ($p=0.653$). Overall, post-hoc tests showed that patients significantly improved over the whole learning period (Δ=27.1±20.9 Nm/rad, $p<0.001$), between baseline and 1 week of practice (Δ=19.1±17.6 Nm/rad, $p<0.001$), and between 1 week and 3 weeks of practice (Δ=8.0±10.5Nm/rad, $p<0.001$). Appendix 9.3 lists details of all post-hoc tests. Intention-to-treat analysis yielded similar results (Table 9.4A), suggesting that attrition did not influence results.

9.2. Secondary outcomes

Table 9.3A summarizes the sway (root-mean-square error degrees) in single- and dual-task conditions per group, while Table 9.3B presents the results of the Timed-up-and-Go test and the mobility subscale of the Utrecht Scale for Evaluation of Rehabilitation.

Regarding single-task sway, both the external (Δ=0.93±1.97°) and internal group (Δ=1.37±2.37°) showed substantial improvements after three weeks of practice (main effect of time, $p<0.001$; Table 9.4A). However, results also showed that the external group showed larger initial improvements than the internal group (significant group by time interaction, $p=0.031$). Specifically, post-hoc tests showed that the external group significantly improved between baseline and 1 week of practice (Δ=0.97±1.72°, $p=0.016$), but did not further improve afterwards (Δ=-0.05±0.84°, $p=0.779$). The internal group showed the opposite pattern. It did not significantly improve in the first week (Δ=0.60±2.14°, $p=0.320$), but only achieved significant improvements between 1 and 3 weeks of practice (Δ=0.77±1.29°, $p=0.018$; Appendix 9.3). Results were similar with intention-to-treat analyses (Table 9.4A).

With regard to dual-task sway, both the external (Δ=1.28±1.77°) and internal group (Δ=0.69±1.66°) showed improvements after three weeks of practice (main effect of time, $p<0.001$; Table 9.4A). However, this improvement in dual-task sway did not differ between groups ($p=0.330$; Table 9.4A). Overall, post-hoc tests showed that patients significantly improved over the whole learning period (Δ=0.98±1.88°, $p<0.001$), and showed near-significant improvements between baseline and 1 week of practice (Δ=0.62±2.03°, $p=0.060$), and between 1 week and 3 weeks of practice (Δ=0.36±1.43°; $p=0.076$). Intention-to-treat analysis yielded similar results (Table 9.4A).

With regard to the clinical tests of general balance and mobility, after three weeks of practice the external and internal group both showed significant improvements in single-task ($\Delta_{external}$=5.55±6.07 seconds; $\Delta_{internal}$=5.95±6.60 seconds) and in dual-task ($\Delta_{external}$=5.78±7.99

seconds; $\Delta_{internal}$=6.27±7.43 seconds) Timed-up-and-Go performance. They also both showed significant improvements ($\Delta_{external}$= 10.2±6.0 points; $\Delta_{internal}$=7.2±6.2 points) in the mobility subscale of the Utrecht Scale for Evaluation of Rehabilitation (main effects of time, *p*'s<0.001; Table 9.4B). For all three outcomes, these improvements did not differ between groups (*p*≥0.094). Intention-to-treat analyses yielded similar results for all three outcomes (Table 9.4B).

Table 9.3. Summary of balance board (A) and clinical test (B) results (mean±standard error). Data presented here concern the raw unadjusted data for patients for whom complete data was available (i.e., per protocol; N=51).

A. Balance Board Measures			
Threshold Stiffness	***Test Session***	***Internal Focus***	***External Focus***
Threshold Rotational Stiffness (Newton meter/radian)	*Baseline*	44.08±7.13	40.00±5.05
	1 week	25.03±5.01	20.89±3.89
	3 weeks	15.64±4.46	14.21±3.45
Single-Task Sway			
Single-Task sway (degrees RMSE)	*Baseline*	2.48±0.51	2.34±0.36
	1 week	1.46±0.41	0.78±0.16
	3 weeks	0.57±0.17	0.66±0.20
Single-Task Handrail Support (number of times)	*Baseline*	1.56±0.33	1.77±0.30
	1 week	0.70±0.25	0.58±0.21
	3 weeks	0.46±0.17	0.23±0.09
Dual-Task Sway[a]			
Dual-Task sway (degrees RMSE)	*Baseline*	2.13±0.48	2.58±0.42
	1 week	1.30±0.39	1.15±0.33
	3 weeks	0.69±0.19	0.72±0.19
Dual-Task Handrail Support (number of times)	*Baseline*	1.35±0.26	2.08±0.44
	1 week	0.98±0.37	0.67±0.20
	3 weeks	0.50±0.24	0.60±0.21
Tone-counting dual-task costs (%)	*Baseline*[b]	9.15±3.78	4.63±3.45
	1 week	5.23±3.56	3.34±2.17
	3 weeks	1.14±3.42	0.48±2.13
B. Clinical Balance & Mobility Tests			
Single-Task Timed-up-and-Go	***Test Session***	***Internal Focus***	***External Focus***
Single-Task Timed-up-and-Go(s)	*Baseline*	20.45±2.48	17.89±2.37
	3 weeks	14.64±2.55	12.34±1.66
Dual-Task Timed-up-and-Go[a]			
Dual-Task Timed-up-and-Go (s)	*Baseline*	22.04±2.60	19.11±2.48
	3 weeks	16.18±2.50	12.81±1.54
Timed-up-and-Go -tone-counting dual-task costs (%)	*Baseline*	5.18.±3.41	1.77±3.56
	3 weeks	7.67±3.49	-1.08±4.94
USER-Mobility			
USER-Mobility	*Baseline* [c]	23.54±1.41	23.27±1.26
	3 weeks[d]	30.71±1.05	33.44±0.35

NB: [a] One internal group member excluded as outlier; [b] No data for 1 internal group member due to malfunctioning microphone; [c] No data for 1 internal group member; [d] No data for 1 external and 3 internal group members; Abbreviations: RMSE=Root-mean-square error; USER=Utrecht Scale for Evaluation of Rehabilitation;

Table 9.4. Results of per protocol (N=51) and intention-to-treat (N=63) GEE-analyses of balance board (A) and clinical test results (B).

A. Balance Board Measures	**Per protocol (N=51)**		**Intention-to-treat (N=63)**	
Threshold Stiffness	**Wald χ2**	**p**	**Wald χ2**	**p**
Group *(Internal, External)*	1.47	0.226	2.594	0.107
Time *(Baseline, 1 week, 3 weeks)*	85.82	**<0.001**	116.73	**<0.001**
Group x Time	0.85	0.653	1.04	0.595
Weight[a]	9.64	**0.002**	20.52	**<0.001**
Single-Task Sway				
Group *(Internal, External)*	0.40	0.526	0.00	0.952
Time *(Baseline, 1 week, 3 weeks)*	15.46	**<0.001**	23.29	**<0.001**
Group x Time	6.92	**0.031**	6.40	**0.041**
Handrail Support	11.57	**<0.001**	14.01	**<0.001**
Dual-Task Sway[b]				
Group *(Internal, External)*	0.27	0.603	0.71	0.400
Time *(Baseline, 1 week, 3 weeks)*	14.33	**0.001**	25.06	**<0.001**
Group x Time	2.22	0.330	2.76	0.252
Handrail Support	4.97	**0.026**	6.89	**0.009**
Tone-counting dual-task costs	6.47	**0.011**	3.92	**0.048**
B. Clinical Balance & Mobility Tests	**Per protocol (N=51)**		**Intention-to-treat (N=63)**	
Single-Task Timed-up-and-Go	**Wald χ2**	**p**	**Wald χ2**	**p**
Group *(Internal, External)*	0.65	0.421	1.16	0.282
Time *(Baseline, 3 weeks)*	40.96	**<0.001**	51.96	**<0.001**
Group x Time	0.05	0.823	0.14	0.710
Dual-Task Timed-up-and-Go[b]				
Group *(Internal, External)*	0.84	0.359	1.38	0.240
Time *(Baseline, 3 weeks)*	35.42	**<0.001**	45.05	**<0.001**
Group x Time	0.00	0.970	0.01	0.907
Tone-counting dual-task costs	5.11	**0.024**	5.44	**0.020**
USER-Mobility[c]				
Group *(Internal, External)*	1.07	0.302	3.33	0.068
Time *(Baseline, 3 weeks)*	89.27	**<0.001**	99.44	**<0.001**
Group x Time	2.81	0.094	2.59	0.108

NB: [a]Sensitivity analysis revealed the effect of group (p=0.611) and group by time interaction (p=0.653) to be similar when weight was excluded from the stiffness analysis; [b]One internal group member was excluded as outlier, but sensitivity analyses showed that the group by time interaction remained nonsignificant when this patient was included (p=0.574); [c]Baseline USER mobility scores unavailable for 6 patients. Abbreviations: RMSE=Root-mean-square error; USER=Utrecht Scale for Evaluation of Rehabilitation;

9.3. Influence of patient characteristics on effectiveness of focus instructions

We found that patients with comparatively good balance and sensory functioning, and with low attentional capacity generally showed stronger improvements in balance board performance with external than with internal instructions.

First, baseline Berg Balance Scale score predicted whether patients improved their threshold rotational stiffness more with external or with internal focus instructions (Waldχ^2=29.64, p<0.001). In the internal group, worse Berg Balance Scale scores were predictive of greater improvements in threshold stiffness (B=-1.665). This pattern was less pronounced for the external group (B=-0.392).

Second, sensory functioning of the lower extremities (Revised Nottingham Sensory Assessment) modified learning on all three balance board outcomes (threshold rotational stiffness: Waldχ^2=17.69, p=0.001; single-task sway: Waldχ^2=21.59, p<0.001; dual-task sway: Waldχ^2=6.709, p=0.082). In the external group, better sensory functioning predicted greater improvement in threshold stiffness (B=0.485) and single-task sway (B=0.152). In contrast, in the internal group lower sensory functioning predicted greater improvement in threshold stiffness (B=-1.410) and single-task sway (B=-0.061). Effects on dual-task sway were similar but less distinct.

Finally, attention (D2-attention test) scores predicted whether dual-task sway improved most with external or internal focus instructions (Waldχ^2=7.843, p=0.049). In the external group, lower attention scores predicted greater improvement in dual-task sway (B=-0.013). In the internal group, by contrast, better attention scores predicted greater improvement in dual-task sway (B=0.008).

4. Discussion

This RCT found that the external group did not show greater improvements in the primary outcome, threshold rotational stiffness, compared to the internal focus group. Analysis of the secondary outcome measure of single-task sway revealed that the external group showed greater improvements early in learning after 1 week, but not after 3 weeks of practice. Yet, the external group did not show enhanced automaticity: Both groups showed comparable improvements in dual-task sway. In line with this, both groups reported a similar amount of declarative movement-related knowledge (Appendix 1), which also indicates that balance performance was similarly automated.[47,56] Finally, the lack of group differences in the Timed-up-and-Go and Utrecht Scale for Evaluation of Rehabilitation suggests that both attentional focus interventions had similar clinical benefits. Overall, external focus instructions did not result in greater improvements in motor skill and automaticity compared to internal focus instructions in rehabilitating stroke patients.

Our results are different from those of the majority of studies in healthy adults, which reported that external focus interventions result in superior motor skill and dual-task performance.[56,57,86,87,99,208,256,258,302] One explanation for this stems from the single-task sway analysis. This suggested that external instructions may accelerate learning in the very short term – within the first week of practice – but not in the longer term – after three weeks of practice. Notably, in healthy adults, balance board studies that reported greater improvements in performance with an external focus typically concerned practice periods of a few days.[87,208,256] Possibly, benefits in healthy adults will also decrease or even disappear with prolonged practice.

From a clinical viewpoint, one could speculate that accelerated learning with external focus instructions may increase patients' feelings of competence,[312] motivation, and self-efficacy, and could eventually shorten inpatient rehabilitation duration. Note, though, that accelerated learning was not observed in stiffness and automaticity, and clinical benefits were similar for both groups. Also, patients found it more difficult to use external focus instructions, which possibly decreases motivation. This difficulty with focusing externally may be related to patients' overall strong inclination to consciously control their movements, which is evidenced by patients' high scores on the Movement-Specific Reinvestment Scale (Table 2).[28,29,134]

The effect modification analyses partly confirmed our hypothesis that the effects of focus instructions would be dependent on patients' motor functioning, sensory functioning, cognition, and conscious control inclination. Specifically, external instructions resulted in greater improvements in balance board performance for patients with comparatively good balance and sensory functioning, while internal instructions were more effective for patients with larger impairments. This skill-dependent effect of attentional focus was also found in a previous study that compared the immediate effects in stroke patients.[212] Wulf et al.[87] argued that an internal focus hinders learning because it disrupts automaticity. Our findings suggest that this is only the case if some degree of sensory function and motor skill has been established in the first place (cf. Masters and Maxwell[93]). In addition, when it comes to improving dual-tasking, we found that patients with more severe attentional deficits benefitted more from external focus instructions than from internal focus instructions. This is in line with the idea that an internal focus is more attention-demanding than an external focus.[86,87] Focusing internally would therefore be more easy for patients with intact attentional capacity, especially in dual-task situations when resources need to be shared with an additional cognitive task.

For rehabilitation practice, these results imply that a tailored use of attentional focus instructions may be more effective than an exclusive reliance on external focus instructions. This study suggests that a patients' motor, sensory, and attentional functioning may be important. However, we do not know how therapists should weigh these different characteristics; e.g. what to do if a patient has both good balance *and* large attentional capacity? A challenge for future research is to replicate our analyses, investigate other possibly relevant factors such as imagery capacity,[313] and explore how different factors interact.

To the best of our knowledge, this is the first RCT that compared attentional focus instructions on motor skill and automaticity in rehabilitating stroke patients. Our results seem generalizable to the larger stroke population, given the large heterogeneity in terms of patient characteristics. Recent reviews have emphasized the need for motor learning research to improve on reporting, methodology, sample size, and statistics.[96,97,314] Accordingly, we pre-registered the study design, a-priori defined the primary and secondary outcomes, and blinded outcome assessment and group allocation. Further, this study involved a comparatively large number of patients and an adequately long practice period. Finally, intention-to-treat analyses confirmed the robustness of our results to drop-outs and missing cases.

A limitation is the absence of a control group that received no specific instructions, making it impossible to assess whether the focus instructions hindered or promoted learning. Also, we only used one specific standardised focus instruction per group. These exact same instructions have been used extensively in prior research in healthy adults and elderly,[87,208] larger contrast between the interventions might have been achieved by using a larger set of attentional focus instructions. Another limitation was that it is impossible to blind the person providing the intervention to group allocation. A third point concerns the clinical relevance of the chosen tasks. While often used for research purposes,[87,208,256] the balance task primarily taxes mediolateral balance control in a laboratory setting. Future studies may compare the effects of focus instructions on walking, or more complex (e.g., perturbation) and functional balance tasks.[238] Fourth, we did not include a retention test after a couple of weeks or months, and thus could not compare the longer-term retention of skill improvements. A final issue concerns our effect modification analyses. In contrast to the factors planned for this analysis, the sensory functioning test (Revised Nottingham Sensory Assessment) was added to our analysis plan when the study was already underway. During a meeting on a related topic, a physical therapist argued that patients may compensate for impaired sensory functioning with conscious, internally focused control. Although our data seem to confirm this hypothesis, further research is needed to replicate these findings. This is especially true given that our sample size was powered for the analysis of our primary outcome variable only

5. Conclusions

No overall benefit was found of external focus instructions over internal focus instructions for improving balance skill and automaticity after stroke. For clinical practice, our results suggest that it may be more effective to tailor instructions to the individual patient, rather than uniformly use external instructions for all patients.

6. Acknowledgements

The authors thank Chantal Nieuwenhuizen, Rafaël Brouwer, and Rosalie Denneman for their contribution to data collection and pilot measurements. We also would like to thank Roelof van Ouwerkerk, Bas Vermeeren, Thijs Zwinnen, and Micha Paalman (department of Physics and Medical Technology, VU Medical Centre, Amsterdam, The Netherlands) and Bert Clairbois and Siro Otten (Department of Human Movement Sciences, VU University, Amsterdam, The Netherlands) for their contributions to the development of the balance board and software.'

7. Funding

This project was funded by the Revalidatiefonds (number: R2015042; www.revalidatiefonds.nl). The funding party had no involvement in data collection, analysis, or interpretation. It was also not involved in writing the paper or in the decision to submit it for publication.

Appendix 9.1. Results of manipulations checks

Adherence to instructions

Patients were able to maintain their focus throughout the trial, and found the provided instructions effective for improving their performance (average scores on all three checks < 5.0 cm). The external group did tend to rate it more effortful to focus as instructed (mean=3.23, SE=0.32; $t(49)=1.860$, $p=0.070$, $d=0.260$) and to maintain this focus throughout each trial (mean=4.08, SE=0.31; $t(49)=1.737$, $p=0.089$, $d=0.243$) compared to the internal group (mean=2.30, SE=0.38; and mean=3.18, SE=0.42; respectively). Both groups judged the effectiveness of instructions similar ($mean_{External}=3.37$, SE=0.33 vs. $mean_{Internal}=2.88$, SE=0.36, respectively; $t(49)=1.01$, $p=0.318$, $d=0.141$).

Amount of movement-related declarative knowledge of balance board performance

The external and internal group reported a similar number of movement-related rules at baseline (mean=2.42, SE=0.24, vs. mean=2.04, SE=0.28, respectively), after 1 week (mean=2.19, SE=0.22, vs. mean=1.96, SE=0.23, respectively) and after 3 weeks (mean=2.23, SE=0.31, vs. mean=1.84, SE=0.28, respectively; t's(49)≤1.049, p≥0.299, d≤0.150). The number of movement-related rules did also not change over time in either group (t's(24-25)≤0.894, p's≥0.380, d's≤0.179).

Appendix 9.2. Threshold rotational stiffness over time

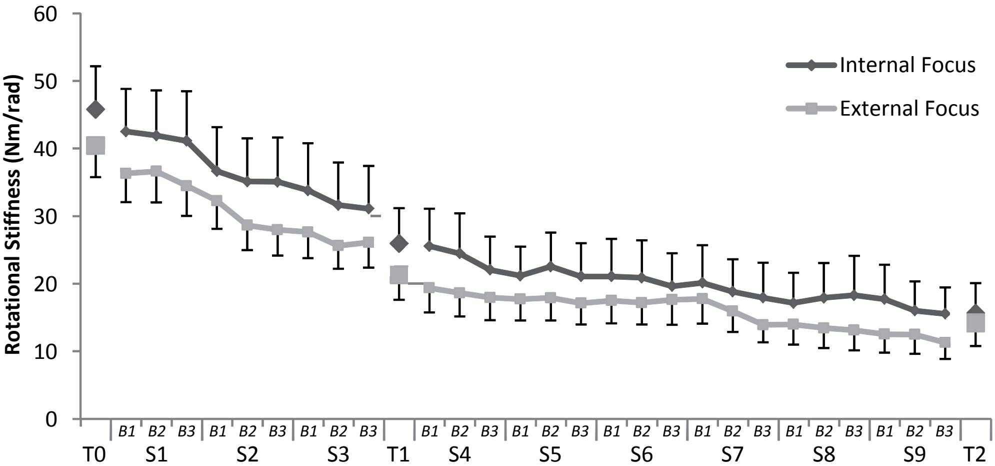


Figure A.9.2. Development of threshold rotational stiffness (Mean Nm/rad ± Standard Error) over time for all patients who completed the whole 3-week training period (per protocol; N=51). Results are presented for each test session (T0-T2), and per block (B1-B3) of each practice session (S1-S9) for both groups. Lower values indicate better performance.

Appendix 9.3. Details of post-hoc tests per analysis

Analysis			
Threshold rotational stiffness	**Both groups combined**	**External group**	**Internal group**
Baseline vs. 1 week	$t(50)=7.735$ $p<0.001$ $d=1.083$	N/A	N/A
1 week vs. 3 weeks	$t(50)=5.463$ $p<0.001$ $d=0.765$	N/A	N/A
Baseline vs. 3 weeks	$t(50)=9.248$ $p<0.001$ $d=1.295$	N/A	N/A
Single-task sway	**Both groups combined**	**External group**	**Internal group**
Baseline vs. 1 week	N/A	$t(25)=2.887$ $p=0.016$ $d=0.566$	$t(24)=1.405$ $p=0.320$ $d=0.281$
1 week vs. 3 weeks	N/A	$t(25)=-0.280$ $p=0.779$ $d=0.055$	$t(24)=2.976$ $p=0.018$ $d=0.595$
Baseline vs. 3 weeks	N/A	$t(25)=2.403$ $p=0.016$ $d=0.471$	$t(24)=2.898$ $p=0.020$ $d=0.580$
Dual-task sway	**Both groups combined**	**External group**	**Internal group**
Baseline vs. 1 week	$t_{T0\text{-}T1}(49)=1.769$ $p=0.060$ $d=0.310$	N/A	N/A
1 week vs. 3 weeks	$t_{T0\text{-}T2}(49)=1.035$ $p=0.076$ $d=0.254$	N/A	N/A
Baseline vs. 3 weeks	$t(49)=3.698$ $p<0.001$ $d=0.528$	N/A	N/A

NB: N/A = not applicable;

Chapter 10

Epilogue

1. Thesis summary

The ability to perform dual-tasks while moving is often impaired in people with stroke. The aim of this thesis was to investigate the potential of implicit motor learning interventions to target this problem. The rationale was that implicit motor learning should result in relatively automatic movements and thereby enhance dual-task performance in stroke patients. To ensure a comprehensive assessment, the thesis comprised three main parts: reviews of the current evidence, observational studies of current rehabilitation practice, and experimental studies to determine the immediate and longer-term effects of an implicit- versus explicit learning intervention on motor skill, automaticity, and dual-task performance.

In the first part, which is covered by **Chapters 2 and 3**, I systematically reviewed the current evidence regarding implicit motor learning in healthy adults and people with stroke. Specifically, the results of **Chapter 2** suggest that implicit motor learning interventions have a small benefit for dual-task performance compared to explicit motor learning interventions in healthy adults. In addition, the results in **Chapter 3** indicate that the ability for implicit motor learning seems largely preserved after stroke. Importantly, however, in both chapters the strength of the evidence is weak, due to a significant lack of reporting on group selection, randomization, and blinding procedures. Other important limitations of the current literature are the short intervention periods and small samples involved. Also, the results of **Chapter 3** reveal a clear lack of studies that assess implicit motor learning in clinically relevant, dynamically complex motor tasks in people with stroke (e.g., gait or balance tasks); all but one study investigated implicit learning by means of the serial reaction time paradigm.

The second part of this thesis focused on how implicit and explicit motor learning strategies are currently applied within rehabilitation practice, both by patients and physical therapists themselves. First, the results of **Chapter 4** show that it is possible to use a self-report questionnaire – the Movement-Specific Reinvestment Scale – to validly and reliably measure a stroke patient's general inclination to use conscious (explicit) motor control in daily life. Results further confirm the idea that stroke patients are more strongly inclined to do so than their healthy peers. In **Chapter 5** this scale was used in a different sample of rehabilitating stroke patients. Results show that patients with stronger inclinations for conscious control experience greater reductions in gait speed when they concurrently need to perform a tone-counting dual-task. This provides indirect evidence for the hypothesis that conscious control impairs dual-tasking after stroke. In **Chapter 6**, I show that physical therapists use a balanced mix of more implicit (external focus) instructions and more explicit (internal focus) feedback during inpatient rehabilitation. Interestingly, therapists adapt their use of instructions to the individual patient, using more externally focused statements for patients with a longer length of stay and with a stronger conscious control inclination. Also, therapist-interviews reveal that they tried to rely more on implicit, external focus strategies for patients with cognitive impairments and relatively intact sensory functioning. As such, the results of **Chapter 6** nuance the findings of **Chapter 5**, as they suggest that – rather than being negative per se – explicit, conscious motor control could be beneficial to performance and learning in particular subgroups of patients.

The third part of this thesis focused on the actual effects of one particular implicit learning intervention – external focus instructions – on movement automaticity and dual-tasking in stroke. First, the results of **Chapter 7** show that external focus instructions can be used to induce implicit motor learning. Specifically, healthy adults show significantly faster leg-stepping performance and increased automaticity with external focus instructions compared to with internal focus instructions. Most importantly, results show that external focus instructions also enhance dual-task performance compared to internal focus instructions. In **Chapter 8**, however, these results cannot be replicated in chronic stroke patients – even though the exact same paradigm is used. Thus, external focus instructions do not benefit patients' leg-stepping performance, automaticity, or dual-task performance. The absence of group level effects seems due to the fact that patients do not uniformly respond to the focus instructions; in this study, patients with weaker conscious control inclinations and better motor skill performed better with external- compared to internal focus instructions (and vice versa). Finally, in **Chapter 9** a randomized controlled trial is described to compare the effectiveness of external and internal focus instructions on *learning* of a more clinically relevant balance board task in rehabilitating stroke patients. Results show a small benefit of external instructions for single-task motor performance after one week of practice. However, after 3 weeks of practice both the external- and internal focus group show similar improvements in balance skill and dual-task performance. Most importantly – similar to **Chapter 8** – the effects of attentional focus seem to depend on certain patient characteristics. In particular, external focus instructions result in more effective learning for patients with better baseline motor skill and sensory functioning, and with worse attention capacity.

Overall, the results of this thesis do not support the hypothesis that implicit motor learning uniformly benefits motor skill, automaticity of movement, and dual-task performance in people with stroke. Rather, the findings in **Chapters 6, 8, and 9** suggest that implicit and explicit motor learning interventions need to be tailored to the individual patient. A patient's motor skill, sensory functioning, attention capacity, and conscious control inclination all seem to influence whether an implicit- or explicit intervention is most effective. In the remainder of this discussion section I will discuss these results in more detail. The aim is to provide leads for future research on this topic, but also to give some (preliminary) guidance for clinical application.

2. What works for whom? Can we tailor implicit and explicit motor learning interventions during rehabilitation after stroke?

The main implication of this thesis for clinical practice is that therapists should strive toward a more tailored approach to motor learning in rehabilitation. Intuitively, this seems plausible. Given the large heterogeneity in the aetiology and clinical manifestations of stroke, it would actually be surprising if one particular motor learning intervention would be superior for all patients in all circumstances. However, the large heterogeneity in (constellations of) impairments simultaneously underlines the complexity of determining the best-fitting motor learning intervention for an individual stroke patient. Successful tailoring thus requires that a therapist knows which patient factors are important, but also how different factors are to be weighed.

While they are by no means conclusive, the results of this thesis shed some light on these issues. Results of Chapters 6, 8, and 9 fairly consistently point to four patient characteristics as potential effect modifiers. These were: Motor skill, cognition/attention, sensory function, and conscious control inclination. In Chapter 6, all four emerge as factors that therapists seem to take into account when selecting either external- (more implicit) or internal focus (more explicit) motor learning strategies in daily practice. Furthermore, all are also found to modify the effects of these interventions in either or both Chapters 8 and 9 – the chapters where I compare the immediate and longer-term effects on motor and dual-task performance.

Figure 10.1 summarizes the results of these three chapters. Importantly, this figure also shows that *how* these four patient characteristics purportedly influence the effectiveness of external and internal focus interventions may depend on the desired timeframe in which effects should be achieved (i.e., immediate vs. longer-term), as well as other task constraints (i.e., single- vs. dual-task conditions). To illustrate this, consider the first characteristic: motor skill. Results of Chapters 6, 8, and 9 suggest that patients' who have better initial motor skill will benefit more from implicit than from explicit interventions. The reverse is also true – patients with worse skill are more likely to benefit from explicit interventions. Importantly, these effects are only evident for *single*-task motor performance and learning; no effects are evident regarding dual-task performance and learning. Below, I will further discuss these findings per characteristic separately in more detail.

	Observational Study (Chapter 6)	Experimental Studies (Chapter 8)		Experimental Studies (Chapter 9)	
Findings concern:	*Experiential knowledge & behavior of physical therapists*	*Immediate effects on motor performance*		*Long-term effects on motor learning*	
Task Condition: / **Patient Characteristic:**	General	Single-Task	Dual-Task	Single-Task	Dual-Task
Motor skill	IL>EL	IL>EL	IL=EL	IL>EL	IL=EL
Attention/ Cognition	IL<EL	IL=EL	IL>EL	IL=EL	IL<EL
Sensory Function	IL>EL	*N/A*	*N/A*	IL>EL	IL>EL
Conscious control inclination	IL>EL	IL<EL	IL=EL	IL=EL	IL=EL

Figure 10.1. Patient characteristics in relation to the relative effectiveness of explicit (internal focus; EL) and implicit (external focus; IL) motor learning interventions per study.
For each study it is presented how each of the four patient characteristics were related to the relative effectiveness of implicit (external focus; IL) and explicit (internal focus; EL) interventions. For the results of Chapters 8 and 9 a further distinction is made between the effects on single-task and dual-task performance.
NB: EL: Explicit motor learning; IL: Implicit motor learning; N/A: not assessed;

2.1. Motor skill

Therapists generally use more explicit, internal focus strategies in early rehabilitation phases, and increase their use of implicit, external focus strategies as rehabilitation progresses (Chapter 6). This also matches their self-reported strategy of switching to more implicit strategies as a patient's motor skill develops. The findings in Chapters 8 and 9 are consistent with this way of working: Patients with less developed motor skills show superior motor performance and learning with internal focus instructions, whereas external focus instructions seem more effective for patients with relatively good motor skill (Figure 10.1).[††] However, as shown in Figure 10.1, motor skill only influences the effects on *single*-task motor performance and learning; no effects are observed for dual-task performance and learning.

The finding that the effects of implicit and explicit motor learning interventions differ as a function of stroke patients' motor skill is not a surprise finding. Patients' motor skill was identified as one of the most important factors to consider when opting for implicit or explicit strategies in a recent Delphi-study among experts in motor learning research.[315] Further, there is also experimental work in healthy adults that points to an effect-modifying role of an individual's level of motor skill. Several studies have found that novices show superior performance when they focus internally, whereas skilled individuals benefit more from an external focus.[217,316] Relatedly, experiments by Beilock and colleagues [125,317] also showed that motor performance of novices is enhanced when they focus on the task at hand, but is degraded when they are distracted. In contrast, they observed an opposite pattern of results in skilled performers.

My findings and those in healthy adults fit traditional theories of skill acquisition. Fitts and Posner[46] posited that early in learning (in the verbal-cognitive phase) movements need to be consciously controlled per se. Only with continued practice does motor control gradually become more automatic. This would explain why promoting explicit, conscious control of movement through explicit learning is most beneficial for patients with greater motor impairments - as well as for novice healthy performers. In fact, Wulf and colleagues imply this possibility in their explanation for the generally superior motor learning effects of external focus strategies in healthy adults.[87,254] Their constrained action hypothesis states that an internal focus intervention hinders performance and learning because it disrupts automaticity. Yet, inherent in this reasoning is the assumption that a certain basic level of motor skill is already established (see also Masters and Maxwell[93]). While this may be true in many healthy adults, the results of this thesis suggest that this is arguably not the case for many stroke patients – especially early in rehabilitation.

†† It is interesting to note that these results are consistent across studies, even though different assessments of motor skill are used in Chapter 8 (Fügl-Meyer Assessment – lower extremity subscale) than in Chapter 9 (Berg Balance Scale). The reason for using different assessments is that I wanted to use motor skill tests that were most relevant for the motor tasks performed (Chapter 8: Leg-stepping task; Chapter 9: Balance board task).

Clinical message: Consider to predominantly promote explicit learning using internal focus of attention strategies for patients with worse motor skill. Switch to predominantly implicit, externally focused strategies for patients with better developed motor skill. Of note, when the main rehabilitation goal is to improve dual-task performance, motor skill does not seem to be an important factor in choosing for a particular motor learning strategy.

2.2. Cognition/Attention

Therapists most frequently (+/-66%) mention patients' cognitive capacity as important factor when deciding between implicit and explicit strategies (Chapter 6). Specifically, they state that they use more implicit motor learning interventions for patients with greater cognitive impairments. In Chapters 8 and 9 one particular cognitive domain– attention capacity – is found to influence whether external or internal focus instructions are most effective. Also, in both studies this is only observed for dual-task conditions. This suggests that attention capacity only becomes an important effect modifier when it is sufficiently taxed, such as in dual-task conditions.

The way in which attention capacity modifies the effectiveness of focus instructions on dual-task performance differs between Chapters 8 and 9. Intriguingly, for patients with larger attention capacity an external focus results in superior *immediate* dual-tasking improvements (Chapter 8), while an internal focus results in superior *long-term* dual-tasking improvements (Chapter 9). Theoretically, based on the constrained action hypothesis one would predict internal focus instructions to be best suited for individuals with good attention capacity. This because internal focus instructions are thought to be more attention-demanding than external focus instructions.[87,254] However, this thesis suggests that this prediction only holds true when patients are given sufficient time to practice with their assigned focus (i.e., 3 weeks in Chapter 9).

The discrepancy in short- and long-term results may be due to the focus familiarity of patients. In both chapters 8 and 9, patients generally reported a strong inclination for conscious motor control in daily life. As such, they were more familiar with using an internal focus of attention,[240] and therefore probably needed to invest a greater amount of attentional resources to comply with the relatively unfamiliar external focus.[215,318] In Chapter 8 patients only perform a few trials with each focus of attention, which gives them little opportunity to get accustomed to the 'new' external focus strategy. Hence, in this study, patients with greater attention capacity are better equipped to use an external focus than patients with smaller attention capacity. In Chapter 9, patients practice their focus instruction over a period of 3 weeks. This gives them ample time to get familiar with either instruction. Without differences in focus familiarity between groups,[‡‡] patients with greater attention capacity now improve the most with internal focus instructions.[§§] In short, these results imply that internal focus instructions are best suited for individuals with good attention capacity – but only when there is no confounding effect of focus familiarity.

Besides attention capacity, other cognitive domains (i.e., working memory and executive function) do not modify the effects of external and internal focus of attention in Chapters 8 and 9. Especially the absence of an effect of working memory is notable, considering its central role in implicit motor learning.[44,93] This might be due to the fact that only one relatively simple (internal or external) focus instruction is used in these studies. It seems that working memory needs to be taxed more profoundly for it to constrain learning. A recent study Buszard et al.[73,] showed that providing multiple explicit instructions benefits motor learning of children with superior working memory capacity, but actually impairs learning of children with relatively poor working memory capacity.[cf 319] Thus, working memory capacity may also act as effect modifier, depending on the number of explicit instructions/rules provided.

Clinical message: When the main goal is to improve dual-task performance of patients, their attention capacity seems relevant. More implicit, external focus instructions seem more effective for patients with attention capacity impairments. Yet, given that many patients have a strong inclination for conscious control,[28,29,134] it might take a few practice sessions for them to get used to this unfamiliar focus strategy.

2.3. Sensory function

In Chapter 6, several therapists state that they make more use of explicit (internal focus) strategies for patients with impaired body awareness. Indeed, sensory function turns out to be a quite strong effect modifier in Chapter 9; patients with lower scores on a screening test of touch and proprioception show greater improvements in balance board performance when they practice with internal focus instructions compared to external focus instructions. Effects are consistent for single- and dual-task measures (Figure 10.1).

‡‡ This was evidenced by patients' self-reported ability to perform their focus instructions in Chapter 9. After the first session, the internal focus group scored significantly better (23.2±21.7) compared to the external group (37.0±22.5; $t(49)=-2.22$, $p=0.03$; lower scores indicate less difficulty). After the last session, however, scores were similar between groups (internal: 23.2±26.1; external: 28.7±20.5; $t(48)=-0.829$, $p=0.41$). Only the external focus group showed a reduction in perceived difficulty of complying with the instructions ($t(24)=2.050$, $p=0.05$).

§§ Please also note that the patients in Chapter 9 were subacute stroke patients, while those in Chapter 8 were chronic stroke patients. The latter might have found it especially difficult to adjust to a 'new' strategy, because they had used their conscious control strategies for such a long period of time (±10 years since stroke).

In healthy adults, intact somatosensory feedback is essential for implicit motor control. A powerful illustration hereof is the famous case of Ian Waterman.[320,321] Due to a gastric flu infection he experienced peripheral nerve damage, resulting in permanent selective loss of all sense of touch and proprioception. Although his motor nerves were spared, he was no longer able to move due to this loss of peripheral feedback. The only way in which he could perform movements was by looking directly at the limbs involved, and investing significant cognitive effort in consciously monitoring and executing the desired skill. After prolonged practice he managed to remaster basic daily motor skills, such as standing upright and walking, and even the ability to drive a car. However, conscious visual control of movement always remains necessary.

In a sense, patients with stroke can suffer from the same problems as Ian Waterman. Accordingly, it seems that when patients no longer have an accurate sense of their body, conscious (visual) control of movement is needed to compensate for this. For those patients, it would make sense to use explicit, internal focus instructions to help them consciously control their movements. In contrast, external focus instructions will be less efficient, as they direct patients' attention away from their body and thereby prevent the patient from making the necessary adaptations to his/her movements (see also Toner & Moran[322] and Shusterman[323]). Further, external instructions will likely also be more attention-demanding: Patients are effectively asked to focus on the effects of their movements *on top of* focusing internally (which they simply need to do regardless). This would explain why internal focus instructions appear superior both for single- *and* dual-task performance in patients with more severe sensory impairments.

The potential role of sensory functioning has received almost no attention in experimental research on implicit motor learning in general and focus of attention in particular. Results of Chapter 9 do seem to fit with a study by Vidoni and Boyd.[324] They explored the relation between proprioceptive deficits (i.e., a limb-position matching task) and motor learning ability in chronic stroke patients. Their paradigm typically induces implicit motor learning: Patients learned to track a continuously moving stimulus on a screen, by moving a joystick with their hemiparetic hand. Unbeknownst to the patients, the stimulus first moved randomly and then followed a specific pattern in each trial (a version of the serial-reaction time paradigm described in Chapter 1). After practice, patients had become significantly better at tracking the repeated segment than at tracking the random segments. However, learning improvements were smaller for patients with greater proprioceptive impairments. This suggests that implicit learning strategies are dependent on the integrity of patients' proprioception. Still, no comparison was made with an explicit learning intervention in this paper, and therefore we must be cautious with this interpretation of results.

Clinical message: More explicit, internal focus strategies seem most beneficial for patients with substantial sensory impairments. Consider to switch towards relatively more implicit, external focus strategies for patients with minimal or no sensory impairments.

2.4. Conscious control inclination

As described in Chapter 6, therapists use relatively more implicit (external focus) strategies for patients with stronger conscious control inclinations. This characteristics only modified the immediate effects of focus instructions on single task motor performance in Chapter 8 (Figure 10.1). This suggests that patients perform best when they receive instructions that fit their conscious control inclinations. Yet, this effect may be restricted to single-task performance and short time scales: In Chapter 9 conscious control inclination does not modify the effects of attentional focus instructions on learning a new balance task over a 3-week period.

Research into the effect modifying role of conscious control inclinations (or focus preferences) in healthy people largely concurs with the findings in Chapter 8. Several studies have shown that motor performance is enhanced when an individual receives focus instructions that he/she prefers or is familiar with.[215,318,325, cf 299] Studies by Tse et al.[214] and Maurer and Munzert et al.[215] further suggest that these effects may also transfer to short-term learning. Tse et al.,[214] for instance, had young children practice a dart throwing task in one practice session, either using an internal or external focus of attention. At a delayed retention test one week later, those children with a strong conscious control inclination showed greatest improvements in throwing accuracy when they had practiced with an internal focus of attention. Conversely, children with low conscious control inclinations improved most when they had practiced with an external focus instruction. Maurer and Munzert essentially found the same results in healthy adults who practiced a golf-putting task (two practice sessions). In conclusion, it seems best to align focus instructions with an individual's conscious control inclination, but only when effects are to be achieved on short time scales (i.e., within one week).

Time scale may in part explain the absence of an effect modifying role of conscious control inclination in Chapter 9. Different from Chapter 8, and the studies in healthy adults, patients had sufficient time (three weeks) to get accustomed to their particular focus instruction. This likely resulted in an increased task-specific focus familiarity that rendered patients' general conscious control inclination irrelevant (see also section 2.2. "Cognition/Attention"). This idea is supported by the data in Chapter 9: Patients overall had a strong conscious control inclination at baseline (M=21.5±6.1). Accordingly, they generally found it more difficult to perform an external focus than an internal focus of attention (p<0.05). Yet, after practice this difference in perceived difficulty to focus as instructed had disappeared, even though patients overall still reported a high conscious control inclination (M=19.5±5.4) after the intervention.

Clinical message: For short term effects on single-task motor performance, it may be best to provide more explicit, internal focus instructions to patients with stronger conscious control inclinations – and vice versa. However, given sufficient practice, patients' general conscious control inclination seems less relevant.

2.5. Successful tailoring in practice: How to weigh the relative importance of different factors?

I described how motor skill, attention capacity, sensory function, and conscious control inclination each may separately predict whether implicit or explicit motor learning interventions will be more effective for a particular stroke patient. However, in clinical practice this will often result in conflicting predictions. For instance, what to do if a patient presents with severe motor impairments (suggesting a more explicit, internal focus strategy) *and* severely impaired attention capacity (suggesting a more implicit, external focus strategy)? A key question therefore is: Is there an objective way to judge the relative importance of different effect modifiers when deciding upon a particular motor learning strategy?

Unfortunately, in general for now the answer must be 'no'. This is uncharted territory. Based on the results of Chapter 9 I did make a decision tree in which a preliminary attempt is made to weigh different patient characteristics – yet this tool now first needs to be put to the test in future studies (see the "Future Directions" section for a detailed discussion). Thus, awaiting this and further evidence, for now I would recommend therapists to rely on their professional experience and intuition to select an appropriate motor learning strategy. The results of this thesis do provide some leads to guide them in this process. That is, one step that may help reduce the number of potentially relevant factors is to consider the therapeutic goal (i.e., improve single- or dual-task performance) and desired timeframe (i.e., immediate effects vs. longer-term effect). For instance, when the goal is to achieve long-term improvements in dual-task performance, a patient's attention capacity and sensory function seem relevant, whereas motor skill and conscious control inclination do not (or less so; Figure 10.1).

Clinical message: Therapists should rely on their clinical expertise to weigh the patient's characteristics in order to select proper motor learning strategies. One step that may help to reduce the number of potentially relevant factors is to consider the therapeutic goal (i.e., mainly improve single- or dual-task performance) and desired timeframe in which effects are to be achieved (i.e., immediate effects vs. longer-term effects after multiple practice sessions). Figure 10.1 could give some guidance for this selection.

3. Future directions

3.1. Tailoring

This thesis showed that motor learning interventions could help to improve motor skills and dual-tasking after stroke, but that there is likely not one single approach that will always work best for all patients. An important issue for future research is therefore to further investigate if (and how) we can successfully tailor implicit and explicit interventions to the individual patient. Specifically, future studies are needed that:

1. Validate the four effect modifiers identified in this thesis (motor skill, attention capacity, sensory function, conscious control inclination) and determine whether results generalize to different motor skills (e.g., gait or reach-to-grasp) and/or implicit learning interventions (i.e., analogy-, errorless, and dual-task learning)
2. Explore the importance of other possibly effect modifiers, such as working memory[73] and motor imagery capacity[313]
3. Explore how different combinations of impairments influence the effectiveness of implicit and explicit motor learning interventions after stroke

Ultimately these combined efforts might enable us to develop general guidelines for tailored use of implicit and explicit motor learning interventions post-stroke. To give a tangible example of how these efforts could benefit clinical practice, consider Figure 10.2. Here, I present a decision tree that I created based on the results of the RCT described in Chapter 9. With this tool therapists could tailor implicit and explicit learning strategies when aiming to achieve long-term improvements in balance board performance. I will briefly illustrate how I did this, and how therapists might use this tool.

As a first step, a therapist needs to decide whether his/her primary aim is to achieve long-term improvements in single-task (Figure 10.2.A) or dual-task performance (Figure 10.2.B). Next, the therapist is only needs to consider those characteristics that are relevant to this aim. For instance, when aiming to improve single-task performance, the two characteristics of interest are motor skill (BBS)[232] and sensory functioning (NSA).[231] Subsequently, the therapist needs to determine whether the patient meets specific cut-off values for these variables. Using the regression analyses reported in Chapter 9, I determined that external focus instructions resulted in superior improvements in single task performance compared to internal focus instructions for patients with NSA scores >74 and BBS scores > 46. Finally, the therapist needs to weigh these characteristics. For this decision tree, I did this by assigning each patient a score of 0 (both variables indicate internal focus to be superior), 1 (one indicates an internal focus, the other indicates an external focus), or 2 (both suggest an external focus). I then plotted the learning improvements in rotational stiffness for these three groups of patients. This revealed that an external focus resulted in superior improvements in single-task performance for patients with a score of 2 (both BBS and NSA suggest an external focus), while an internal focus was superior for patients who scored 0-1. This can also be seen in the decision tree – only in case of two positive answers is an external focus recommended (Figure 10.2.A). The decision tree in panel B (for dual-task performance) was made using the same approach.

Admittedly, the resulting decision tree in Figure 10.2 is highly task-specific (e.g., designed for one particular balance paradigm) and needs to be validated in future research. Retrospective application on the data in Chapter 9 confirmed that patients who received their "optimal" focus instruction according to this decision tree achieved significantly greater improvements in rotational stiffness and dual-task sway compared to patients who did not (Mann-Whitney U; p's ≤ 0.035). Yet, to properly validate this decision tree, we need to test whether the same results are obtained when the tool is used prospectively.

A final remark concerns the limitations of the use of simple rule-based decision trees in clinical practice. Such tools should be used to guide therapists, and serve as an extra tool to extend their own intuitions and clinical reasoning. As eloquently argued by Dreyfus,[326] experts (in any domain) possess intuitive experiential knowledge that is often superior to – and cannot easily be captured by – simple, rule-based procedures. As such, the role of decision trees (like the one presented in Figure 10.2) should be to give guidance to physical therapists' decision making, but certainly not prescribe it. For instance, a decision tree may be very useful to start from for a therapist who starts treatment with a new patient, or in case the current repertoire of motor learning instructions and strategies used does not seem to be particularly effective, and a change of strategy may be needed.

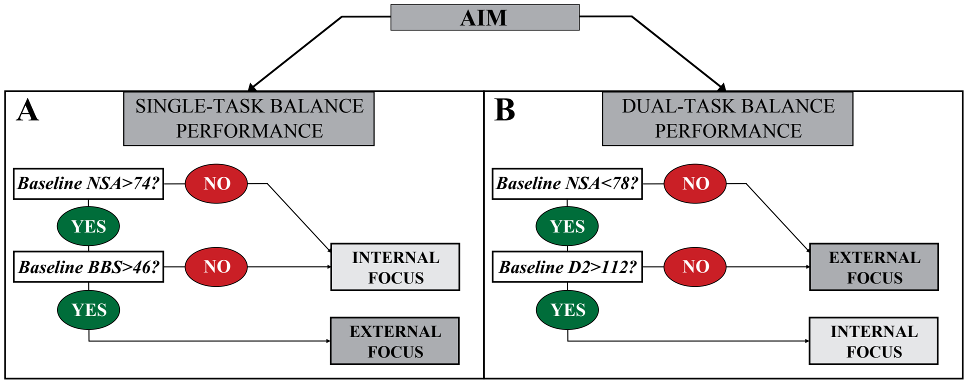


Figure 10.2 Example of decision tree for tailoring focus instructions for the balance board task described in Chapter 9. First, therapists decide whether their main aim is to achieve long-term improvements in single-task (A) or dual-task performance (B). This provides therapists with guidance as to which patient characteristics are relevant, and which are not. Next, based on specific cut-off values on these relevant patient characteristics an external or internal focus strategy is recommended. Retrospective application of the decision tree presented in Figure 10.2 on the data in Chapter 9 confirmed that patients who received their "optimal" focus instruction achieved significantly greater improvements in rotational stiffness and dual-task sway compared to patients who did not (Mann-Whitney U; *p's* ≤ 0.035).
NB: BBS = Berg Balance Scale (0-56; higher scores indicate better balance capacity); D2 = D2-Attention test (0-300; higher scores indicate better attention capacity);[230] NSA = Nottingham Sensory Assessment (0-80; higher scores indicate better sensory function);

3.2. Dual-task training

Future studies may also revisit the paradigm of dual-task training as intervention to improve dual-tasking after stroke. In recent years, several studies in stroke and elderly have reported beneficial effects of dual-task training regimes (i.e., practicing motor and cognitive tasks simultaneously) versus single-task practice schedules (where only the motor task is practiced).[35,36] These results are usually explained using the framework of Kramer who posited that dual-task training improves a person's ability to appropriately divide attention between two tasks.[327,328] However, we would then expect to see significant transfer of learning to new dual-task combinations – which is typically not the case.[38,39] An alternative explanation for the results of dual-task training studies is that they covertly compare implicit with explicit learning. That is, for patients in the dual-task group their working memory is occupied by a secondary task. This restricts their opportunities to process movement related information, resulting in relatively implicit motor learning.[41,55] By contrast, in these studies the single-task training intervention typically consists of performing several motor tasks in isolation - and apparently without specific constraints put in place to prevent learners from focusing on their movements. It is well known that such an approach generally induces explicit learning.[41,49]

This raises the question whether dual-task training would also be superior to single-task training when the latter is explicitly¶¶designed to induce implicit learning (e.g., by means of external focus instructions).

4. Strengths and limitations

A strength of this thesis is that complementary methods were used to approach the topic of implicit motor learning in rehabilitation after stroke. Combining systematic reviews, observational studies and experimental studies made it possible to link findings from the extant literature and experimental research to observations of clinical practice. For instance, with regard to tailoring of motor learning, similar patterns of results emerged from the observation of clinical practice (Chapter 6) and experimental studies (Chapters 8-9). This further strengthens the confidence in these findings, but also facilitates implementation of the results of this thesis back into practice. Another example is the critical evaluation of the current literature with the systematic reviews, as presented in Chapters 2 and 3. Most importantly, it was found that studies typically involve small samples and short intervention periods, are often not pre-registered, and lack detailed description of group selection, randomization, and blinding. Combined, these issues undermine the validity and reproducibility of (implicit) motor learning research.[97,129] This analysis of the current literature was essential to carefully design the randomized controlled trial in Chapter 9, and circumvent these methodological pitfalls as much as possible.

An important limitation of thesis is that the experimental studies were restricted to one implicit motor learning intervention: external focus instructions. This was based on the widespread evidence for, and use of external focus interventions in sports science and practice,[57,76,77] and the fact that this intervention is gaining more and more attention in neurorehabilitation education and practice.[78,79] However, it remains to be seen whether the findings of this thesis also apply to other implicit learning interventions, such as analogy-, errorless- and dual-task learning. There is currently at least one randomized controlled trial under way that compares the effects of analogy and explicit learning in chronic stroke – its results are much anticipated.[329]

A second limitation of the studies described in this thesis (and of implicit motor learning research in general) is the lack of objective, direct manipulation checks that measure whether the purported implicit interventions really resulted in minimal conscious control of movement. Most studies (including several in this thesis) have assessed performers' movement related knowledge or dual-task performance for this purpose (Chapters 2 and 3). The presumption is that people who move more automatically can tell less about their movements, and show better dual-task performance. While plausible, these are indirect measures; verbal reports are

¶¶ No pun intended.

collected after the fact, while dual-tasking is influenced by factors such as task prioritization and working memory capacity. EEG measurements and pupillometry are promising alternatives. For instance, increased conscious motor control is accompanied by increased coherence between left-lateralised verbal-analytical brain regions (T3-electrode) and central premotor brain regions (Fz).[68,69,127] Also, it is well known that pupil dilation is positively associated with conscious mental effort.[330,331] While this has typically been shown in cognitive tasks, we recently found similar results in a whole-body balance task.[332]

A third limitation concerns this thesis' recommendations for a tailored approach to motor learning in rehabilitation after stroke. At the start of this PhD project it was not my primary aim to investigate this issue. While there seems to be a theoretical and empirical basis for my findings (as discussed in section 10.2) results are based on cross-sectional and retrospective analyses. To obtain stronger evidence, it is necessary to investigate whether prospectively allocating patients to a particular intervention based on their characteristics optimizes motor learning (e.g., as per the decision tree in Figure 10.2). Hence, results of this thesis can best be considered as starting points for clinicians and future research into tailored motor learning approaches.

A final limitation concerns the dual-task assessments used in the experimental studies. That is, only one or two types of dual-tasks were used, these being a letter fluency task and/or tone-counting task, respectively. Using a range of different cognitive dual-tasks would have allowed a more comprehensive assessment of dual-tasking ability. On the other hand, a strength of the dual-tasks used is that they all tax patients' executive function. These classes of dual-tasks have been shown to trigger the greatest dual-task interference while moving.[333]

5. Conclusion

This thesis investigated the effects of implicit motor learning through external focus instructions in people with stroke. No evidence was found that implicit motor learning uniformly benefits motor skill, automaticity of movement, and dual-task performance compared to explicit motor learning. It was shown that implicit and explicit motor learning interventions could both be effective, depending on the stroke patients' motor and sensory function, attention capacity, and conscious control inclination. This implies that motor learning should be tailored to the individual patient for optimal effects.

Nederlandse Samenvatting

Bij mensen met een cerebrovasculair accident (CVA), is er hersenweefsel beschadigd als gevolg van verstoorde bloedcirculatie in de hersenen, bijvoorbeeld door een blokkade (infarct) of scheur van een bloedvat (bloeding). Een CVA, ook wel "beroerte" genoemd, kan grote gevolgen hebben voor het motorisch en cognitief functioneren van een patiënt. Veel patiënten zijn bijvoorbeeld niet meer goed in staat om zelfstandig te staan, lopen of schrijven, en hebben daarnaast vaak ook problemen met het richten, vasthouden en verdelen van hun aandacht. Na een CVA volgen patiënten daarom een intensief multidisciplinair revalidatietraject om deze vaardigheden weer aan te leren, ofwel te compenseren met andere beweegstrategieën. In deze periode boeken patiënten doorgaans grote vooruitgang in hun motorisch functioneren. Echter, een groot probleem voor veel patiënten is dat zij moeite blijven houden om tijdens het bewegen extra taken te kunnen uitvoeren, zoals het voeren van een gesprek of het letten op het verkeer tijdens het lopen. Het niet goed kunnen uitvoeren van dit soort "dubbeltaken" is niet alleen belemmerend voor hun dagelijks functioneren, maar kan ook leiden tot onveilige situaties en een verhoogd valrisico.

In dit proefschrift heb ik onderzocht of we de dubbeltaakprestatie van CVA-patiënten kunnen verbeteren door hen op een andere manier opnieuw te leren bewegen. Patiënten zijn namelijk erg geneigd om hun bewegingen heel bewust en stap-voor-stap uit te voeren, en worden hiertoe vaak ook gestimuleerd door de behandelaar. Zulk "expliciet" leren brengt echter een grote cognitieve belasting met zich mee, en dit leidt er mogelijk toe dat de patiënt minder aandachtcapaciteit over heeft om een extra taak te kunnen uitvoeren. Een logisch alternatief lijkt daarom om het oefenen zoveel mogelijk "impliciet" te maken. Hierbij worden de oefeningen zo gestructureerd en geïnstrueerd dat de patiënt zo min mogelijk bewust over de bewegingsuitvoering hoeft na te denken. Dit kan bijvoorbeeld door de patiënt zo min mogelijk fouten te laten maken tijdens het bewegen (foutloos leren), met behulp van beeldspraak te instrueren (analogie leren), of te laten letten op de effecten van hun beweging (externe focus). Dit soort impliciete leerinterventies zouden ervoor moeten zorgen dat de patiënten meer automatisch bewegen, en daarmee meer aandachtcapaciteit over houden voor de uitvoering van dubbeltaken.

Het hoofddoel van dit proefschrift was om te bepalen of impliciet leren leidt tot meer automatische bewegingen en betere dubbeltaakprestatie bij CVA-patiënten vergeleken met expliciet leren. Het proefschrift bestaat uit drie delen, namelijk: (1) systematische literatuurstudies van het huidige bewijs voor de effectiviteit van verschillende impliciete leerinterventies bij gezonde mensen en CVA-patiënten; (2) observationele studies waarin het gebruik van impliciet leren in de huidige revalidatiepraktijk onder de loep wordt genomen; en (3) experimentele studies waarin is onderzocht wat de directe en lange termijn effecten zijn van één impliciete motorische leerinterventie – externe focus instructies – op motorische vaardigheden, bewegingsautomatisering, en dubbeltaakprestatie bij mensen na een CVA.

In het eerste deel, dat de **hoofdstukken 2 en 3** beslaat, staan systematische literatuurstudies beschreven waarin ik een analyse heb gemaakt van het huidige bewijs voor de effectiviteit van impliciet en expliciet leren bij gezonde jonge mensen en CVA-patiënten. De resultaten van **hoofdstuk 2** suggereren dat impliciete leerinterventies een klein positief effect hebben op de dubbeltaakprestatie bij gezonde mensen. Daarnaast blijkt uit **hoofdstuk 3** dat het vermogen tot impliciet motorisch leren grotendeels intact lijkt te zijn bij CVA-patiënten. Echter, uit beide hoofdstukken kwam duidelijk naar voren dat de zeggingskracht van de huidige literatuur beperkt is. De meeste studies zijn van matige methodologische kwaliteit, hebben slechts een korte interventieduur en betreffen kleine groepen deelnemers. Daarnaast bleek uit **hoofdstuk 3** dat er duidelijk behoefte is aan studies waarin de effecten van impliciet leren worden onderzocht bij motorische taken met directe klinische relevantie, zoals loop- of balanstaken.

In het tweede deel van dit proefschrift is geanalyseerd hoe impliciete en expliciete motorische leerinterventies in de praktijk worden gebruikt, zowel door fysiotherapeuten als door CVA-patiënten zelf. De resultaten van **hoofdstuk 4** laten zien dat je met een simpele vragenlijst – de Movement-Specific Reinvestment Scale – valide en betrouwbaar kan meten in hoeverre een patiënt geneigd is om bewuste (expliciete) bewegingscontrole te gebruiken in het dagelijks leven. De resultaten bevestigden ook het vermoeden dat CVA-patiënten veel meer geneigd zijn om dit te doen dan gezonde leeftijdsgenoten. In **hoofdstuk 5** blijkt dat patiënten die meer geneigd zijn om hun bewegingen bewust te controleren grotere moeite hebben om snel en accuraat te reageren op geluiden tijdens het lopen. Dit is indirect bewijst voor de hypothese dat bewuste, expliciete bewegingscontrole een negatief effect heeft op de dubbeltaakprestatie. Uit **hoofdstuk 6** blijkt dat fysiotherapeuten bij de behandeling van hun CVA-patiënten gebruik maken van een mix van impliciete (externe focus) en expliciete (interne focus) motorische leerstrategieën. Bovendien blijkt dat therapeuten hun gebruik van instructies afstemmen op de individuele patiënt. Impliciete strategieën worden meer gebruikt bij patiënten met een sterkere neiging tot bewuste bewegingscontrole, en bij wie het revalidatieproces al verder gevorderd was. Therapeuten geven daarnaast ook aan dat ze hun gebruik van leerstrategieën aanpassen aan de motoriek, cognitie, en proprioceptie van de patiënt. De resultaten van **hoofdstuk 6** nuanceren daarmee die van **hoofdstuk 5**, omdat ze suggereren dat expliciete, bewuste bewegingscontrole bij sommige patiënten wel degelijk een positief effect op de prestatie kan hebben.

In het derde deel van dit proefschrift heb ik de daadwerkelijke effecten onderzocht van één specifieke impliciete interventie – externe focus instructies – op de bewegingsautomatisering en dubbeltaakprestatie van CVA-patiënten. Uit **hoofdstuk 7** blijkt dat externe focus instructies geschikt zijn om impliciet leren te bewerkstelligen. Gezonde volwassenen voeren een staptaak significant sneller en automatischer (vloeiender) uit wanneer ze dit doen met een externe focus instructie dan wanneer ze dit doen met een interne focus instructie. Bovendien blijkt dat de externe focus instructie hen ook beter in staat stelt om een extra taak uit te voeren tijdens deze staptaak. Echter, in **hoofdstuk 8** konden deze resultaten niet worden gerepliceerd bij een groep chronische CVA-patiënten, ondanks het feit dat precies dezelfde experimentele opzet is gebruikt als in **hoofdstuk 7**: Externe focus instructies hebben geen positief effect op de stapprestatie, automatisering, en dubbeltaakprestatie van de patiëntengroep. Dit komt mogelijk doordat het effect van de instructies erg verschilt van patiënt tot patiënt; externe focus instructies lijken met name goed te werken voor patiënten met relatief goede motorische vaardigheid, slechte aandachtcapaciteit en een zwakke neiging om hun bewegingen bewust te controleren. In **hoofdstukken 7 en 8** zijn echter alleen de directe effecten geanalyseerd van externe en interne instructies, dus dit roept de vraag op of deze resultaten stand houden als patiënten over langere tijd oefenen met de verschillende instructies. In **hoofdstuk 9** is daarom een gerandomiseerde gecontroleerde studie beschreven. Revaliderende CVA-patiënten leerden een meer klinisch relevante balansbordtaak aan gedurende een periode van 3 weken, ofwel met externe focus instructies ofwel met interne focus instructies. Uit de resultaten blijkt dat beide groepen evenveel vooruitgang hebben geboekt in balansprestatie en dubbeltaakprestatie na de volledige oefenperiode. Daarnaast blijkt dat – net als in **hoofdstuk 8** – dat de effecten van de instructies af lijken te hangen van bepaalde karakteristieken van de patiënt: Patiënten met relatief goede motorische vaardigheid en proprioceptie, en relatief slechte aandachtcapaciteit profiteerden meer van externe dan van interne instructies (en vice versa).

Op basis van de resultaten van dit proefschrift is mijn conclusie dat impliciet motorisch leren niet *altijd* een positief effect zal hebben op de motorische vaardigheid, bewegingsautomatisering, en dubbeltaakprestatie van *alle* CVA-patiënten. De bevindingen van **hoofdstukken 6, 8 en 9** suggereren dat impliciete en expliciete interventies beiden effectief kunnen zijn, maar dat het gebruik van deze interventies dient te worden afgestemd op de individuele patiënt. Het lijkt belangrijk om hierbij rekening te houden met de patiënts motorische vaardigheid, cognitie, proprioceptie en neiging tot bewuste bewegingscontrole.

Dankwoord

Na ruim 6 jaar is mijn proefschrift eindelijk af. Dat dit überhaupt is gelukt is te danken aan het nuttigen van ongezonde hoeveelheden koffie, maar vooral aan de hulp, steun (en broodnodige afleiding) van een heleboel mensen.

Allereerst wil ik mijn promotieteam bedanken, bestaande uit de promotoren **Erik Scherder** en **Coen van Bennekom**, en copromotoren **Han Houdijk**, **John van der Kamp** en **Erny Groet**.

Beste **Erik**, enorm bedankt voor je steun en motiverende begeleiding in de afgelopen jaren. Ook al was je agenda nog zo vol, je was altijd beschikbaar voor overleg als ik je nodig had. Ik vond het heel fijn dat je altijd verder keek dan het project zelf, en de tijd nam om juist ook te bespreken hoe het met mij ging. Je was onmisbaar om de grote lijnen van mijn proefschrift in het oog te houden, en de belangrijkste aanjager van de RCT die ik uiteindelijk als slotstuk heb uitgevoerd – en waar ik stiekem het meest trots op ben. Het is voor een groot deel aan jou te danken dat ik een verlenging van mijn aanstelling heb kunnen krijgen om dit project goed af te kunnen ronden. Erg bedankt hiervoor, en voor je aanstekelijke enthousiasme.

Beste **Coen**, bedankt dat je me het vertrouwen en de vrijheid gaf om mijn project voor een groot deel zelfstandig naar eigen inzicht in te richten. Als tweede promotor was je meer op de achtergrond bij mijn proefschrift betrokken, maar je was uitermate belangrijk om de rode lijn in mijn project te waarborgen. Alhoewel het onderwerp motorisch leren wat verder afstaat van jouw interessegebied, wist je desondanks altijd razendsnel tot de kern te komen, en de vinger op zere plek leggen als er ergens iets niet helemaal klopte met een onderzoeksvoorstel of artikel. Ook heb ik, als niet-medicus, veel van je geleerd over het doen van klinisch onderzoek. Dank voor dit alles.

Beste **Han en John**, ik had me geen betere copromotoren kunnen wensen. **John**, een van de redenen dat ik een promotie ben gaan doen is dat ik in 2010 bij jou terecht kwam om mijn bachelor scriptie te schrijven. Dat voelde voor mij toen eerlijk gezegd een beetje als een "moetje"; ik wilde helemaal niet het onderzoek in, maar die bachelor moest toch echt afgerond. Ik kwam er echter achter dat ik zowel het schrijven als het onderwerp (motor imagery bij CVA) zo leuk vond dat ik een jaar later toch maar eens bij je ging informeren hoe ik aan een promotieplek in de revalidatie kon komen. Toevallig was er nét een vacature voor een project bij Heliomare waar jij en Han bij betrokken waren, en zo geschiedde (voor de duidelijkheid: ik werd wel gewoon door de mangel gehaald bij de sollicitatie). Ik heb altijd erg genoten van het samenwerken met jou en Han. Jullie gaven me veel vrijheid, maar stuurden ook bij als iets beter kon of moest. Ik heb veel geleerd van jouw brede interesse en je vermogen om ogenschijnlijk heel verschillende concepten aan elkaar te linken. Zo gebeurde het regelmatig dat een groter deel van ons overleg in beslag werd genomen over de overeenkomst tussen theorieën van motorisch leren en het pik-gedrag van kippen, of de werkwijze van koks in toprestaurants, dan inhoudelijk over het onderzoek zelf.

Han, ik kon altijd bij je binnenlopen, zeker als ik zwarte koffie meenam. Hoe druk je het ook hebt, je neemt altijd even de tijd om bij te praten of een van mijn klaagzangen aan te horen - volgens mij begon ik het laatste anderhalf jaar elk overleg wel even een korte update over mijn slaaptekort, sorry daarvoor. Als begeleider was je een ideale tegenhanger van John. Na een kort (of lang) kip-intermezzo was jij vaak degene die ons weer even terugleidde naar het doel van het overleg. Bij deze overleggen wist je trouwens voor een "simpele biomechanicus" – jouw eigen woorden – vaak rake opmerkingen te maken over de wat minder exacte wetenschap van motorisch leren. Daarnaast denk ik met veel plezier terug aan de zeiltochtjes en etentjes met de andere (ex-)promovendi van team Houdijk, en vind het erg leuk dat jij en John uitgebreid op kraamvisite kwamen bij de geboorte van Aya en Jasmine. **Han** en **John**, enorm bedankt voor de fijne samenwerking en al jullie hulp. Ik hoop dat we in de toekomst nog veel projecten samen kunnen doen.

Beste **Erny**, jij bent natuurlijk eigenlijk gewoon mijn derde copromotor. Je bent dan officieel misschien niet gepromoveerd, maar er zijn maar weinig mensen met zoveel kennis en ervaring als klinisch neuropsycholoog. Jouw super georganiseerde werkwijze was uitermate belangrijk om mijn gebrek daaraan te compenseren. Als er ook maar iets geregeld moest worden voor mijn onderzoek binnen Heliomare was het bij wijze van spreke al afgehandeld voordat ik het vroeg. Naast je inhoudelijke bijdrage was je persoonlijke interesse minstens zo belangrijk. Een of twee keer per jaar ging ik even bij je langs om gewoon even te praten over andere zaken dan werk, en die gesprekken vond ik altijd heel prettig. Dank voor deze fijne begeleiding.

Peter Beek, **Sander Geurts**, **Caroline van Heugten**, **Susy Braun** and **Will Young**: Thank you very much for the effort and time that you invested in reading my thesis, and for coming over to Amsterdam for my defense. I am honored to have such a great opposition. I would like to further thank **Will** for giving me the opportunity to work at Brunel. I am really looking forward to work together with you, **Toby**, and **Adam**.

Marinus en **Rens**, ik vind het een eer dat jullie mijn paranimfen zijn. **Rens**, wij zijn al beste vrienden sinds we elkaar hebben leren kennen in de brugklas op Hageveld. Je staat altijd voor me klaar, juist ook in moeilijke tijden of als ik lastige beslissingen moet nemen. De leukste periode van mijn promotie was dan ook het half jaar dat we samen (en met Marinus) onderzoek hebben gedaan in Heliomare. Ik denk met plezier terug aan de fietstochten naar werk, onze Pelican Rouge koffiemomentjes (blegh), en het samen sporten in de pauze. Dit, en het feit dat je me een maand hebt waargenomen, heeft me veel rust gegeven in een toch wel vrij stressvolle periode in mijn leven. Bijzonder dat dit alles ook nog eens heeft opgeleverd dat we nu samen twee artikelen hebben gepubliceerd. **Marinus**, het is plausibel om te stellen dat ook jij een van mijn beste vrienden bent. We kennen elkaar inmiddels ook alweer 16 (!) jaar, en die periode hebben we veel samen meegemaakt. Ooit waren we samen heel fanatiek bezig met atletiek, maar de laatste jaren hebben we ons met datzelfde fanatisme voornamelijk op het onderzoek gestort. In de loop van mijn promotie gingen we steeds vaker samen een dagje werken. Vaak bestonden deze dagen uit véél koffie, drop, wentelteefjes, en vooral uit heerlijk ongenuanceerd commentaar geven op van alles en nog wat, met als afsluiter een rondje hardlopen of – als het echt moest – fietsen. En deze samenwerking was niet alleen leuk, maar ik heb ook (en dit geef ik maar één keer toe natuurlijk) enorm veel van je geleerd. Uiteindelijk hebben we zelfs 3 artikelen samen gepubliceerd. Dus, zoals je zelf zou zeggen, dit was gewoon een "unaniem belachelijk groot succes" ;). **Rens** en **Marinus**, enorm bedankt voor dit alles!

Dit project had zeker nog 10 jaar langer geduurd (en was sowieso veel minder leuk geweest) zonder het harde en goede werk van een groot aantal stagiaires: **Chantal**, **Charlotte**, **Christa**, **Henrieke**, **Manon**, **Menno**, **Mette**, **Nynke**, **Rafaël**, **Renee**, en **Rosalie**, enorm bedankt voor jullie inzet. Ik vond het heel erg leuk en leerzaam om met jullie samen te werken. **Manon**, wij hebben in het laatste jaar van mijn promotie nauw samengewerkt. Ik denk met plezier terug aan je enthousiasme, flexibiliteit en vele traktaties waarmee je ons door lange meetdagen heen sleepte. Wat was ik geschrokken toen ik vorig jaar hoorde dat je ernstig ziek was, en nogmaals toen je begin dit jaar na een aantal maanden de strijd moest opgeven.

Trienke, als "*roomie*", medelid van team Houdijk, én buurvrouw heb je mijn promotie van begin tot eind van dichtbij meegemaakt. Hoe druk je het ook had, we vonden allebei altijd wel tijd om even bij te kletsen, "goeie" koffie te halen bij de koffiecorner (behalve met witte broek!), of soms even een rondje hard te lopen. Vaak stuurde je me resoluut naar huis als ik weer eens onsamenhangend tegen mijn laptop zat te tieren, en dreigde mezelf of de laptop uit het raam te gooien. Tegenwoordig moet ik je missen bij BW, maar ik hoop dat we onze traditionele vrijdagochtend "Badhuis"-momenten nog lang kunnen voortzetten.

Barend, dank voor alle fiets-, hardloop-, en kaasfondue-uitspattingen. Ik vind het altijd heerlijk om met jou zomaar een rondje 'lekker ontspannen' te fietsen, en dan uiteraard compleet gesloopt maar wel voldaan thuis te komen. Onze fietsvakanties in de Alpen met Rens en Marinus zijn altijd een hoogtepunt in het jaar, en ik ben erg blij dat jij bij de organisatie hiervan (zoals met wel meer van onze gezamenlijke activiteiten) altijd het voortouw neemt.

Wouter, met jou heb ik eigenlijk mijn eerste stappen in het 'echte' onderzoek gezet tijdens ons afstudeeronderzoek. Wat een toptijd was dat zeg: ik herinner me vooral dat de dag meestal startte met ruim 2 uur tafeltennissen (dat niveau heb ik nooit meer gehaald) en minstens 1 of 2 afleveringen van South Park – niet zo gek dus dat we er zo'n 1,5 jaar over hebben gedaan.

Ondanks dat je na onze studie helemaal in Hong Kong bent gaan werken zijn we daarna gelukkig altijd goed bevriend gebleven. Ik keek altijd uit naar de keren dat je kwam logeren bij Sheima en mij, en ons bezoek aan jou in Hong Kong vond ik echt geweldig. Ik ben blij dat je nu weer in Nederland woont, en we elkaar hopelijk wat vaker kunnen gaan zien.

Hiernaast heb ik nog veel andere lieve vrienden die ik graag wil bedanken: **Joeri, Joost** en **Rikkert**, bedankt voor alle toepavondjes, waarop jullie ondanks mijn onnavolgbare spel mijn portemonnee vaak flink lichter hebben gemaakt. **Rens (G)**, **Erik**, **Merlin**, en **Wendelien**, jullie zijn zeker in het begin vaak de sjaak geweest als ik weer eens proefpersonen zocht, dank (en sorry) daarvoor. Alle **ZOG teamgenoten**, onze wervelende voetbalwedstrijden, en vooral de hoogstaande analyses achteraf, zijn een van de leukste momenten in de week. **Eric**, sinds de middelbare school zien we elkaar zo ongeveer elk kwartaal om wat te drinken en eten, ik hoop dat we dat nog lang blijven doen, ook in Heidelberg. **Leslie** en **Colin**, met jullie allebei ben ik al zo ongeveer mijn hele leven bevriend. Ik zie jullie niet zo vaak als ik zou willen, maar het betekent veel voor me dat we nog steeds goede vrienden zijn.

Aan alle collega's van **Bewegingswetenschappen**, enorm bedankt voor de fijne tijd. Ik loop inclusief studie alweer 12 jaar rond op de afdeling, en heb me hier altijd goed thuis gevoeld.

Uiteraard verdienen mijn (ex-)collega's van Heliomare een prominente vermelding in dit dankwoord. **Timo**, **Ilse**, **Linda**, **Richard**, **Janneke**, **Judith**, **Saskia**, **Ingrid**, **Maaike**, **Justine** en **Daphne**: Ik heb het altijd enorm naar mijn zin gehad bij R&D, enorm bedankt voor deze fijne tijd en al jullie support. **Timo**, bedankt voor alle leuke fitness- en hardloopsessies tussen de bedrijven door. **Ilse**, ik ga je missen als *roomie* op de VU, en ben erg trots op ons Fysiek Profiel handboek. **Linda**, ik vond het altijd gezellig om even met jou lekker te babbelen over van alles en nog wat. **Richard**, bedankt voor alle ad hoc technische ondersteuning waarmee je me vaak uit de brand hebt geholpen. **Janneke**, ik ga onze thee-momentjes missen waarin we onze gedeelde kinderperikelen bespraken. **Judith**, jij kon me vrijwel altijd direct vertellen hoe en waar ik dingen moest regelen, of had het anders meteen voor me uitgezocht, deze niet zo goed georganiseerde college was daar altijd erg blij mee. **Saskia** en **Ingrid**, we hebben elkaar wat minder lang meegemaakt, maar ik vond jullie fijne collega's. **Maaike**, **Justine** en **Daphne**, jullie zijn nu alweer een tijdje weg, maar we hebben toch heel wat jaartjes samengewerkt. Heel erg bedankt voor de leuke tijd! Tot slot een woord van dank voor alle therapeuten die hebben meegeholpen bij mijn project, en voor mijn huidige collega's van de pijnpoli.

Mama, **Jacinta**, **Neil**, **Tessa**, **Azza**, **Abdallah**, **Alia**, **Hazem**, en lieve **oma**, wat een geluk heb ik dat met zo'n lieve en warme familie en schoonfamilie! Jullie hebben me altijd enorm gesteund, zelf al wisten jullie niet altijd precies waar ik en Sheima nou helemaal mee bezig waren (wij zelf ook vaak niet trouwens). Heel erg bedankt hiervoor, en voor jullie onmisbare hulp met Aya en Jasmine.

Lieve **Aya** en **Jasmine**, bedankt voor jullie lieve lachjes en knuffels die me dwingen om het werk af en toe lekker te laten voor wat het is.

Lieve **Sheima**, je bent de liefde van mijn leven. In de laatste 8 jaar hebben we heel veel meegemaakt samen. Ik had het met niemand anders willen en kunnen doen. Bedankt voor alles. Ik hou van je.

About the author

Curriculum vitae

Elmar Kal was born on March 3th, 1988 in Haarlem, the Netherlands. He obtained his Bachelor's degree in Human Movement Sciences at VU University Amsterdam in 2011. After a small digression to Sports Psychology at the University of Amsterdam, he went back to the VU where he obtained his Master's degree in Human Movement Sciences with a specialization in rehabilitation in 2012 (cum laude). Subsequently, he started his PhD project on implicit motor learning in stroke in September 2012. This project was a collaboration between (what would later become) the Faculty of Behavioural and Movement Sciences of the VU University Amsterdam and Rehabilitation Centre Heliomare in Wijk aan Zee. This project has resulted in multiple publications in international peer-reviewed journals, as well as numerous presentations at national and international conferences. Since January 2018, Elmar works as a lecturer at the Faculty of Behavioural and Human Movement Sciences and University Centre for Behaviour and Movement of the VU. In addition, he works as a researcher at the chronic pain department of Heliomare, where his main role is to manage the clinimetrics database.

List of publications

Papers in international scientific journals

Brouwer R, **Kal E,** van der Kamp J, Houdijk H. Validation of the stabilometer balance test: Bridging the gap between clinical and research based balance control assessments for stroke patients. *Gait and Posture* 2018; Accepted.

Kal E, Houdijk H, van der Kamp J, Verhoef M, Prosée R, Groet E, Winters M, van Bennekom C, Scherder E. Are the effects of internal focus instructions different from external focus instructions given during balance training in stroke patients? A double-blind randomized controlled trial. *Clinical Rehabilitation* 2018; early online: 1-15.

Kal E, Prosée, R, Winters, M, van der Kamp J. Does implicit motor learning lead to greater automatization of motor skills compared to explicit motor learning? A systematic review. *PLoS ONE* 2018; 13(9): e0203591.

Denneman R, **Kal E**, Houdijk H, van der Kamp J. Over-focused? The relation between patients' inclination for conscious control and single- and dual-task motor performance after stroke. *Gait and Posture 2018; 62: 206-213.*

Van Ginneken W, Poolton J, Masters R, Capio C, **Kal E,** van der Kamp J. Comparing the effects of conscious monitoring and conscious control on motor performance. *Psychology of Sport and Exercise* 2017; **30**: 145-152.

Kal E, van den Brink H, Houdijk H, van der Kamp J, Goossens P, van Bennekom C, Scherder E. How physical therapists instruct patients with stroke: An observational study on attentional focus during gait rehabilitation after stroke. *Disability and Rehabilitation* 2017; 40: 1154-1165.

Kal E, Winters M, van der Kamp J, Houdijk H, Groet E, van Bennekom C, Scherder E. Is implicit motor learning preserved after stroke? A systematic review with meta-analysis. *PLoS ONE* 2016; 11: e0166376.

Kal E, Houdijk H, van der Wurff P, Groet E, van Bennekom C, Scherder E, van der Kamp J. The inclination for conscious motor control after stroke: Validating the Movement-Specific Reinvestment Scale for use in inpatient stroke patients. *Disability and Rehabilitation* 2016; 38: 1097-1106.

Brocken J, **Kal E,** & van der Kamp J. Focus of attention in children's motor learning: examining the role of age and working memory. *Journal of Motor Behavior* 2016; 48: 527-534.

Kal E, van der Kamp J, Houdijk H, Groet E, van Bennekom C, Scherder E. Stay focused! The effects of internal and external focus of attention on movement automaticity in patients with stroke. *PLoS ONE* 2015; 10: e0136917.

Kal E, van der Kamp J, Houdijk H. External attentional focus enhances movement automatization: a comprehensive test of the constrained action hypothesis. *Human Movement Science* 2013; 32: 527-39. **(Top 5 most-cited papers in *Human Movement Science* between 2014-2016)**

Papers in Dutch professional journals

Kal, E. Impliciet motorisch leren na CVA: Wat is het bewijs? *Fysiopraxis* 2017; 26, 51.

Kal, E. Effect van instructies op dubbeltaakprestatie na CVA. *Fysiopraxis* 2016; 25: 54.

Van Ginneken W, **Kal E,** van der Eb J, Pijpers R. Is er een verband tussen persoonlijkheid en motoriek? Enkele voorspellingen van ActionType methode getoetst. *Sportgericht* 2013; 67, 7-11.

Presentations at (inter)national conferences

Kal E, Prosée, R, Winters, M, van der Kamp J. Does implicit learning induce more automatic motor performance than explicit motor learning? A systematic review. Oral presentation at the 13th Sports Medical Scientific Year Congress, Ermelo, the Netherlands, 2017.

Kal E, Verhoef M, Houdijk H, van der Kamp J, Groet E, Prosée R, Winters M, van Bennekom C, Scherder E. Are external focus instructions more effective than internal focus instructions to improve balance in stroke patients? A double-blind randomized controlled trial. Poster presentation at the Day of the Physical Therapist, Barneveld, the Netherlands, 2017.

Kal E, van der Kamp J, Houdijk H, Verhoef M, Groet E, Prosée R, Winters M, Scherder E, van Bennekom C. Do external focus instructions benefit motor learning post-stroke? A randomized controlled trial. Poster presentation at the Dutch Congress of Rehabilitation Medicine, Maastricht, the Netherlands, 2017. **(Winner of award for best poster presentation)**

Kal E, van der Kamp J, Houdijk H, Verhoef M, Groet E, Prosée R, Winters M, van Bennekom C, Scherder E. Does an external attentional focus improve motor learning post-stroke? Results of a randomized controlled trial. Poster presentation at the ISPGR World Congress, Fort Lauderdale, USA, 2017.

Kal E. Motor learning in stroke rehabilitation: Does attentional focus matter? Oral presentation at the Kick-off meeting of Amsterdam Movement Sciences, Amsterdam, the Netherlands, 2017.

Kal E, van den Brink H, Houdijk H, van der Kamp J, Goossens P, Scherder E, van Bennekom C. Watch yourself! How do physical therapists use attentional focus instructions in rehabilitation post-stroke?. Poster presentation at the Day of the Physical Therapist, Utrecht, the Netherlands, 2017.

Kal E, van der Kamp J, Roerdink M, Kleynen M, Jie L. Putting motor learning into (neurorehabilitation) practice: A focus on analogies, cueing, and external focus of attention. Organiser of mini-Symposium & oral presentation at the Dutch Congress of Rehabilitation Medicine, Maastricht, the Netherlands, 2016.

Kal E, Winters M, van der Kamp J, Houdijk H, Groet E, Scherder E, van Bennekom C. A systematic review on implicit motor learning in people with stroke: Is there any evidence? Poster presentation at the International Brain Injury Association World Congress, the Hague, the Netherlands, 2016.

Kal E, van den Brink H, Houdijk H, van der Kamp J, Goossens P, Scherder E, van Bennekom. Attentional focus instructions and feedback during gait rehabilitation after stroke. Poster presentation at the Dutch Congress of Rehabilitation Medicine, Rotterdam, the Netherlands, 2015.

Kal E, van der Kamp J, Houdijk H, Groet E, van Bennekom C, Scherder E. Stay focused! The effects of attentional focus on motor and motor-cognitive performance after acquired brain injury. Poster presentation at the ISPGR World Congress, Fort Lauderdale, USA, 2015.

Kal E, van der Kamp J, Houdijk H, Groet E, van Bennekom C, Scherder E. Dual-tasking after acquired brain injury: Does attentional focus matter? Oral presentation at the Congress on Neurorehabilitation and Neural Repair, Maastricht, the Netherlands, 2015.

Kal E, van der Kamp J, Houdijk H, Groet E, Scherder E, van Bennekom. Measuring the inclination for conscious motor control in clinical stroke patients. Poster presentation at the Dutch Congress of Rehabilitation Medicine, Rotterdam, the Netherlands, 2014. **(Winner of award for best poster presentation; Abstract published in *Clinical Rehabilitation* 2015; 29: 306-311.)**

Kal E, van der Kamp J, Houdijk H. Reliability and sensitivity of the Dutch Movement-Specific Reinvestment Scale in clinical stroke patients. Poster presentation at the 5th International state-of-the-art congress on Rehabilitation: Mobility, Exercise and Sports, Groningen, the Netherlands, 2014.

Kal E, van der Kamp J, Houdijk H. External focus of attention enhances movement automatization. Mini-oral presentation at the European College of Sport Science Congress, Amsterdam, the Netherlands, 2014.

Kal E, van der Kamp J, Houdijk H. External focus enhances movement automatization and dual-task performance. Oral presentation at the Dutch Congress of Rehabilitation Medicine, Noordwijkerhout, the Netherlands, 2013.

Kal E, van Ginneken W. The relation between personality and motor behaviour. Oral presentation at the Day of Sports Science, the Hague, the Netherlands, 2012.

References

1. World Health Organisation (WHO). Cause of death statistics 2015. http://www.who.int/mediacentre/factsheets/fs317/en/. Published 2017. Accessed October 21, 2017.
2. Carrera E, Maeder-Ingvar M, Rossetti AO, Devuyst G, Bogousslavsky J. Trends in risk factors, patterns and causes in hospitalized strokes over 25 years: The Lausanne Stroke Registry. *Cerebrovasc Dis*. 2007;24(1):97-103.
3. Nivel Zorgregistratie Eerste Lijn. https://www.volksgezondheidenzorg.info/onderwerp/beroerte. Accessed October 21, 2017.
4. Vaartjes I, Reitsma JB, Berger-Van Sijl M, Bots ML. Gender differences in mortality after Hospital admission for stroke. *Cerebrovasc Dis*. 2009;28(6):564-571.
5. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. *Lancet Neurol*. 2009;8(8):741-754.
6. Tatemichi TK, Desmond DW, Stern Y, Paik M, Sano M, Bagiella E. Cognitive impairment after stroke: Frequency, patterns, and relationship to functional abilities. *J Neurol Neurosurg Psychiatry*. 1994;57(2):202-207.
7. Hackett ML, Köhler S, O'Brien JT, Mead GE. Neuropsychiatric outcomes of stroke. *Lancet Neurol*. 2014;13(5):525-534.
8. Plummer P, Eskes G, Wallace S, et al. Cognitive-motor interference during functional mobility after stroke: State of the science and implications for future research. *Arch Phys Med Rehabil*. 2013;94(12).
9. Baer G, Smith M. The recovery of walking ability and subclassification of stroke. *Physiother Res Int*. 2001;6(3):135-144.
10. Roerdink M, De Haart M, Daffertshofer A, Donker SF, Geurts ACH, Beek PJ. Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. *Exp Brain Res*. 2006;174(2):256-269.
11. Dennis A, Dawes H, Elsworth C, et al. Fast walking under cognitive-motor interference conditions in chronic stroke. *Brain Res*. 2009;1287:104-110.
12. Hyndman D, Ashburn A, Yardley L, Stack E. Interference between balance, gait and cognitive task performance among people with stroke living in the community. *Disabil Rehabil*. 2006;28(13-14):849-856.
13. Plummer-D'Amato P, Altmann LJP, Saracino D, Fox E, Behrman AL, Marsiske M. Interactions between cognitive tasks and gait after stroke: A dual task study. *Gait Posture*. 2008;27(4):683-688.
14. McCulloch K. Attention and dual-task conditions: Physical therapy implications for individuals with acquired brain injury. *J Neurol Phys Ther*. 2007;31(3):104-118.
15. Salbach NM, Mayo NE, Higgins J, Ahmed S, Finch LE, Richards CL. Responsiveness and predictability of gait speed and other disability measures in acute stroke. *Arch Phys Med Rehabil*. 2001;82(9):1204-1212.
16. Canning CG, Ada L, Paul SS. Is automaticity of walking regained after stroke? *Disabil Rehabil*. 2006;28(2):97-102.
17. Beauchet O, Annweiler C, Dubost V, et al. Stops walking when talking: A predictor of falls in older adults? *Eur J Neurol*. 2009;16(7):786-795.
18. Lundin-Olsson L, Nyberg L, Gustafson Y. Stops walking when talking as a predictor of falls in elderly people. *Lancet*. 1997;349(9052):617.
19. Abernethy B. Dual-task methodology and motor skills research: Some applications and methodological constraints. *J Hum Mov Stud*. 1988;14(3):101-132.
20. Kahneman D. *Attention and Effort*. Englewood Cliffs, NJ: Prentice Hall; 1973.
21. Tombu M, Jolicoeur P. A central capacity sharing model of dual-task performance. *J Exp Psychol Percept Perform*. 2003;29(1):3-18.
22. Baddeley A. Working memory: Looking back and looking forward. *Nat Rev Neurosci*. 2003;4(10):829-839.
23. Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. *Mov Disord*. 2008;23(3):329-342.
24. Hyndman D, Pickering RM, Ashburn A. The influence of attention deficits on functional recovery post stroke during the first 12 months after discharge from hospital. *J Neurol Neurosurg Psychiatry*. 2008;79(6):656-663.
25. Hyndman D, Ashburn A. People with stroke living in the community: Attention deficits, balance, ADL ability and falls. *Disabil Rehabil*. 2003;25(15):817-822.

26. Rasquin SMC, Lodder J, Ponds RWHM, Winkens I, Jolles J, Verhey FRJ. Cognitive functioning after stroke: A one-year follow-up study. *Dement Geriatr Cogn Disord*. 2004;18(2):138-144. d
27. Zinn S, Bosworth HB, Hoenig HM, Swartzwelder HS. Executive function deficits in acute stroke. *Arch Phys Med Rehabil*. 2007;88(2):173-180.
28. Orrell AJ, Masters RSW, Eves FF. Reinvestment and movement disruption following stroke. *Neurorehabil Neural Repair*. 2009;23(2):177-183.
29. Kleynen M, Braun SM, Beurskens AJ, Verbunt JA, de Bie RA, Masters RSW. Investigating the Dutch Movement-Specific Reinvestment Scale in people with stroke. *Clin Rehabil*. 2012;27(2):160-165.
30. Barker-Collo SL, Feigin VL, Lawes CMM, Parag V, Senior H, Rodgers A. Reducing attention deficits after stroke using attention process training: A randomized controlled trial. *Stroke*. 2009;40(10):3293-3298.
31. Westerberg H, Jacobaeus H, Hirvikoski T, et al. Computerized working memory training after stroke–A pilot study. *Brain Inj*. 2007;21(1):21-29.
32. Melby-Lervåg M, Redick TS, Hulme C. Working memory training does not improve performance on measures of intelligence or other measures of 'far transfer': evindence from a meta-analytic review. *Perspect Psychol Sci*. 2016;11(4):512-534.
33. Loetscher T, Lincoln N. Cognitive rehabilitation for attention deficits following stroke. *Cochrane database Syst Rev*. 2013;(5):CD002842.
34. Kramer AF, Larish JF, Strayer DL. Training for attentional control in dual task settings: A comparison of young and old adults. *J Exp Psychol Appl*. 1995;1(1):50-76.
35. Plummer P, Villalobos RM, Vayda MS, Moser M, Johnson E. Feasibility of dual-task gait training for community-dwelling adults after stroke: A case series. *Stroke Res Treat*. 2014. doi:http://dx.
36. Yang YR, Wang RY, Chen YC, Kao MJ. Dual-task exercise improves walking ability in chronic stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. 2007;88(10):1236-1240.
37. Plummer-D'Amato P, Villalobos R, Vayda M, et al. Feasibility of training dual task walking after stroke. *Arch Phys Med Rehabil*. 2011;92(10):1717-1718.
38. Silsupadol P, Lugade V, Shumway-Cook A, et al. Training-related changes in dual-task walking performance of elderly persons with balance impairment: A double-blind, randomized controlled trial. *Gait Posture*. 2009;29(4):634-639.
39. Wongcharoen S, Sungkarat S, Munkhetvit P, Lugade V, Silsupadol P. Home-based interventions improve trained, but not novel, dual-task balance performance in older adults: A randomized controlled trial. *Gait Posture*. 2017;52:147-152.
40. Janacsek K, Nemeth D. Implicit sequence learning and working memory: Correlated or complicated? *Cortex*. 2013;49(8):2001-2006.
41. Masters RSW. Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *Br J Psychol*. 1992;83(3):343-358.
42. Johnson L, Burridge JH, Demain SH. Internal and external focus of attention during gait re-education: An observational study of physical therapist practice in stroke rehabilitation. *Phys Ther*. 2013;93(7):957-966.
43. Durham K, Van Vliet PM, Badger F, Sackley C. Use of information feedback and attentional focus of feedback in treating the person with a hemiplegic arm. *Physiother Res Int*. 2009;14(2):77-90.
44. Maxwell JP, Masters RS, Eves FF. The role of working memory in motor learning and performance. *Conscious Cogn*. 2003;12(3):376-402.
45. Anderson J. Acquisition of cognitive skill. *Psychol Rev*. 1982;89(4):396-406.
46. Fitts PM, Posner MI. *Human Performance*. Belmont, CA, US: Brooks/Cole; 1967.
47. Kleynen M, Braun SM, Bleijlevens MH, et al. Using a Delphi technique to seek consensus regarding definitions, descriptions and classification of terms related to implicit and explicit forms of motor learning. *PLoS One*. 2014;9(6):e100227.
48. Maxwell JP, Masters RSW, Kerr E, Weedon E. The implicit benefit of learning without errors. *Q J Exp Psychol Sect A Hum Exp Psychol*. 2001;54(4):1049-1068.
49. Maxwell JP, Masters RSW, Eves FF. From novice to no know-how: A longitudinal study of implicit motor learning. *J Sports Sci*. 2000;18(2):111-120.
50. Poolton JM, Masters RSW, Maxwell JP. The relationship between initial errorless learning conditions and subsequent performance. *Hum Mov Sci*. 2005;24(3):362-378.

51. Nissen MJ, Bullemer P. Attentional requirements of learning: Evidence from performance measures. *Cogn Psychol*. 1987;19(1):1-32.
52. Reber PJ. The neural basis of implicit learning and memory: A review of neuropsychological and neuroimaging research. *Neuropsychologia*. 2013;51(10):2026-2042.
53. Beilock SL, Wierenga SA, Carr TH. Expertise, attention, and memory in sensorimotor skill execution: impact of novel task constraints on dual-task performance and episodic memory. *Q J Exp Psychol A*. 2002;55(4):1211-1240.
54. Lam WK, Maxwell JP, Masters RSW. Analogy versus explicit learning of a modified basketball shooting task: Performance and kinematic outcomes. *J Sports Sci*. 2009;27(2):179-191.
55. Liao C-M, Masters RSW. Analogy learning: A means to implicit motor learning. *J Sports Sci*. 2001;19(5):307-319.
56. Poolton JM, Maxwell JP, Masters RSW, Raab M. Benefits of an external focus of attention: Common coding or conscious processing? *J Sports Sci*. 2006;24(1):89-99.
57. Wulf G. Attentional focus and motor learning: a review of 15 years. *Int Rev Sport Exerc Psychol*. 2013;6(1):77-104.
58. Owen AM, McMillan KM, Laird AR, Bullmore E. N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. In: *Human Brain Mapping*. 2005;25(1):46-59.
59. D'Esposito M. From cognitive to neural models of working memory. *Philos Trans R Soc L B Biol Sci*. 2007;362(March):761-772.
60. McNab F, Klingberg T. Prefrontal cortex and basal ganglia control acces to working memory. *Nat Neurosci*. 2008;11(1):103-107.
61. Lohse KR, Wadden K, Boyd LA, Hodges NJ. Motor skill acquisition across short and long time scales: A meta-analysis of neuroimaging data. *Neuropsychologia*. 2014;59(1):130-141.
62. Gobel EW, Parrish TB, Reber PJ. Neural correlates of skill acquisition: Decreased cortical activity during a serial interception sequence learning task. *Neuroimage*. 2011;58(4):1150-1157.
63. Aizenstein HJ, Stenger VA, Cochran J, et al. Regional brain activation during concurrent implicit and explicit sequence learning. *Cereb Cortex*. 2004;14(2):199-208.
64. Galea JM, Albert NB, Ditye T, Miall RC. Disruption of the dorsolateral prefrontal cortex facilitates the consolidation of procedural skills. *J Cogn Neurosci*. 2010;22(6):1158-1164.
65. Willingham DB, Salidis J, Gabrieli JD. Direct comparison of neural systems mediating conscious and unconscious skill learning. *J Neurophysiol*. 2002;88(3):1451-1460.
66. Grafton ST, Hazeltine E, Ivry R. Functional mapping of sequence learning in normal humans. *J Cogn Neurosci*. 1995;7(4):497-510.
67. Kantak SS, Mummidisetty CK, Stinear JW. Primary motor and premotor cortex in implicit sequence learning - Evidence for competition between implicit and explicit human motor memory systems. *Eur J Neurosci*. 2012;36(5):2710-2715.
68. Zhu FF, Poolton JM, Wilson MR, Maxwell JP, Masters RSW. Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biol Psychol*. 2011;87(1):66-73.
69. Zhu FF, Poolton JM, Wilson MR, Hu Y, Maxwell JP, Masters RSW. Implicit motor learning promotes neural efficiency during laparoscopy. *Surg Endosc Other Interv Tech*. 2011;25(9):2950-2955.
70. Borella E, Carretti B, De Beni R. Working memory and inhibition across the adult life-span. *Acta Psychol (Amst)*. 2008;128(1):33-44.
71. Rieckmann A, Bäckman L. Implicit learning in aging: Extant patterns and new directions. *Neuropsychol Rev*. 2009;19(4):490-503.
72. Chauvel G, Maquestiaux F, Hartley AA, Joubert S, Didierjean A, Masters RSW. Age effects shrink when motor learning is predominantly supported by nondeclarative, automatic memory processes: Evidence from golf putting. *Q J Exp Psychol*. 2012;65(1):25-38.
73. Buszard T, Farrow D, Verswijveren SJJM, et al. Working memory capacity limits motor learning when implementing multiple instructions. *Front Psychol*. 2017;8(AUG).
74. Poolton JM, Masters RSW, Maxwell JP. Passing thoughts on the evolutionary stability of implicit motor behaviour: Performance retention under physiological fatigue. *Conscious Cogn*. 2007;16(2):456-468.
75. Orrell AJ, Eves FF, Masters RSW. Motor learning of a dynamic balancing task after stroke: implicit implications for stroke rehabilitation. *Phys Ther*. 2006;86(3):369-380.

76. Farrow D, Baker J, MacMahon C. *Developing Sport Expertise : Researchers and Coaches Put Theory into Practice*. London; Routledge; 2008.
77. Raab M, Wylleman P, Seiler R, Elbe A, Hatzigeorgiadis A. *Sports and Exercise Psychology Research: From Theory to Practice*. 1st ed. Cambridge, MA, US: Academic Press; 2016.
78. Rogers MW, Martinez KM, McCombe Waller S, Gray VL. Part IV: Sensorimotor impairments and their treatment, Chapter 25: Recovery and rehabilitation of standing balance after stroke. In: Harvey RL, Stein J, Winstein CJ, Wittenberg G, Zorowitz RD, eds. *Stroke Recovery and Rehabilitation*. 2nd ed. New York, NY: Demos Medical Publishing; 2014.
79. Selzer ME, Clarke S, Cohen LG, Kwakkel G, Miller RH. Volume 2: Medical Neurorehabilitation. In: *Textbook of Neural Repair and Rehabilitation*. Cambridge: Cambridge University Press; 2014.
80. ITON. *Brochure Opleiding Neurorevalidatie*. http://www.stichtingiton.nl/wp-content/uploads/2016/11/brochure-Opleiding-Neurorevalidatie.pdf.
81. Masters RSW, Poolton JM. Advances in implicit motor learning. In: Williams AM, Hodges NJ, eds. *Skill Acquisition in Sport: Research, Theory and Practice*. 2nd ed. London: Routledge; 2012:59-77.
82. Farrow D, Baker J, MacMahon C. *Developing Sports Expertise*. 2nd ed. London: Routledge; 2013.
83. Farrow D. *Challenging Traditional Practice Approaches to AFL Kicking Skill Development*.; 2010. http://aussiehockey.com.au/wp-content/uploads/AFL-Kicking-Skill-Development-Report-2010.pdf Accessed 20 jan 2017.
84. Van Ruiven L, Van der Breggen J, Verbeek J, Jonker L. *Onderzoeksrapport Optimale Wedstrijdvorment Pupillen: Onder 6 Tot En Met Onder 12*.; 2016. http://www.knvb.nl/downloads/bestand/6868/onderzoeksrapport-wedstrijdvormen-pupillen-knvb. Accessed 20 Jan 2017.
85. *Visie Op Jeugd Deel 2: Motorische Ontwikkeling En Motorisch Leren (Versie 1.1.)*.; 2015. https://www.knbsb.nl/media/downloads-verenigingsondersteuning/visie-op-jeugd/VisieopJeugdD2-Motorischeontwikkelingenmotorischlerenv1.1.pdf Accessed 20 jan 2017.
86. Kal EC, van der Kamp J, Houdijk H. External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Hum Mov Sci*. 2013;32(4):527-539.
87. Wulf G, McNevin N, Shea CH. The automaticity of complex motor skill learning as a function of attentional focus. *Q J Exp Psychol A*. 2001;54(4):1143-1154. doi:10.1080/0272498014300011.
88. Bahrick HP, Noble M, Fitts PM. Extra task performance as a measure of learning a primary task. *J Exp Psychol*. 1954;48(4):298-302.
89. Logan GD. Skill and automaticity: Relations, implications, and future directions. *Can J Psychol Can Psychol*. 1985;39(2):367-386.
90. Bernstein NA. *Dexterity and Its Development*. (Latash ML, Turvey M, eds.). Hillsdale, NJ: Erlbaum; 1996.
91. Benjaminse A, Welling W, Otten B, Gokeler A. Novel methods of instruction in ACL injury prevention programs, a systematic review. *Phys Ther Sport*. 2015;16(2):176-186.
92. Benjaminse A, Otten B, Gokeler A, Diercks RL, Lemmink KAPM. Motor learning strategies in basketball players and its implications for ACL injury prevention: a randomized controlled trial. *Knee Surg Sports Traumatol Arthrosc*. 2015;25(8):2365-2376.
93. Masters R, Maxwell J. The theory of reinvestment. *Int Rev Sport Exerc Psychol*. 2008;1(2):160-183.
94. Tenenbaum G, Eklund RC. *Handbook of Sport Psychology: Third Edition*. 3rd ed. New York, NY, US: Wiley; 2007.
95. Steenbergen B, van der Kamp J, Verneau M, Jongbloed-Pereboom M, Masters RSW. Implicit and explicit learning: applications from basic research to sports for individuals with impaired movement dynamics. *Disabil Rehabil*. 2010;32(18):1509-1516.
96. Kal E, Winters M, van der Kamp J, et al. Is implicit motor learning preserved after stroke? A systematic review with meta-analysis. *PLoS One*. 2016;11(12):e0166376.
97. Lohse K, Buchanan T, Miller M. Underpowered and overworked: Problems with data analysis in motor learning studies. *J Mot Learn Dev*. 2016;4(1):37-58.
98. Kantak SS, Winstein CJ. Learning-performance distinction and memory processes for motor skills: A focused review and perspective. *Behav Brain Res*. 2012;228(1):219-231.
99. Lohse KR, Sherwood DE, Healy AF. How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Hum Mov Sci*. 2010;29(4):542-555.
100. Higgins JPT, Green S. Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0 [updated March 2011]. In: *The Cochrane Collaboration*. ; 2011.

101. Winters M, Eskes M, Weir A, Moen MH, Backx FJG, Bakker EWP. Treatment of medial tibial stress syndrome: A systematic review. *Sport Med*. 2013;43(12):1315-1333.
102. CEBM Levels of Evidence Working Group. *The 2011 Oxford CEBM Levels of Evidence: Introductory Document*.; 2011.
103. Abdoli B, Farsi A, Barani FH. Comparing the effects of Errorless and Error ful and fixed practices on learning of throwing task. *Eur J Exp Biol*. 2012;2(5):1800-1806.
104. Koedijker JM, Oudejans RRD, Beek PJ. Explicit rules and direction of attention in learning and performing the table tennis forehand. *Int J Sport Psychol*. 2007;38(2):227-244.
105. Koedijker JM, Oudejans RRD, Beek PJ. Table tennis performance following explicit and analogy learning over 10,000 repetitions. *Int J Sport Psychol*. 2008;39(3):237-256.
106. Lam WK, Maxwell JP, Masters R. Analogy learning and the performance of motor skills under pressure. *J Sport Exerc Psychol*. 2009;31(3):337-357.
107. Lam WK, Maxwell JP, Masters RS. Probing the allocation of attention in implicit (motor) learning. *J Sports Sci*. 2010;28(14):1543-1554.
108. Masters RSW, Lo CY, Maxwell JP, Patil NG. Implicit motor learning in surgery: Implications for multi-tasking. *Surgery*. 2008;143(1):140-145.
109. Masters RS, Poolton JM, Maxwell JP. Stable implicit motor processes despite aerobic locomotor fatigue. *Conscious Cogn*. 2008;(1):335-338.
110. Maxwell JP, Masters RSW. External versus internal focus instructions: Is the learner paying attention? *Int J Appl Sport Sci*. 2002;14(2):70–88.
111. Orrell AJ, Eves FF, Masters RSW. Implicit motor learning of a balancing task. *Gait Posture*. 2006;23(1):9-16.
112. Poolton JM, Masters RSW, Maxwell JP. The development of a culturally appropriate analogy for implicit motor learning in a Chinese population. *Sport Psychol*. 2007;21(4):375-382.
113. Sanli EA, Lee TD. What roles do errors serve in motor skill learning? An examination of two theoretical predictions. *J Mot Behav*. 2014;46(5):329-337.
114. Schücker L, Ebbing L, Hagemann N. Learning by analogies: Implications for performance and attentional processes under pressure. *Hum Mov*. 2010;11(2):191-199.
115. Schücker L, Hagemann N, Strauss B. Analogy vs. technical learning in a golf putting task: An analysis of performance outcomes and attentional processes under pressure. *Hum Mov*. 2013;14(2):175-184.
116. Singer RN, Lidor R, Cauraugh JH. To be aware or not aware? What to think about while learning and performing a motor skill. *Sport Psychol*. 1993;7(1):19-30.
117. Totsika V, Wulf G. The influence of external and internal foci of attention on transfer to novel situations and skills. *Res Q Exerc Sport*. 2003;74(2):220-225.
118. Tse ACY, Wong TWL, Masters RSW. Examining motor learning in older adults using analogy instruction. *Psychol Sport Exerc*. 2017;28:78-84.
119. Egger M, Davey Smith G, Schneider M, et al. Bias in meta-analysis detected by a simple, graphical test. *Br Med J*. 1997;315(7109):629-634.
120. Plummer-D'Amato P, Altmann LJP, Reilly K. Dual-task effects of spontaneous speech and executive function on gait in aging: Exaggerated effects in slow walkers. *Gait Posture*. 2011;33(2):233-237.
121. Moher D, Hopewell S, Schulz KF, et al. CONSORT 2010 explanation and elaboration: Updated guidelines for reporting parallel group randomised trials. *Int J Surg*. 2012;10(1):28-55.
122. Vandenbroucke JP, von Elm E, Altman DG, et al. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): explanation and elaboration. *Epidemiology*. 2007;18(6):805-835.
123. Chambers CD. Registered Reports: A new publishing initiative at Cortex. *Cortex*. 2013;49(3):609-610.
124. Dessing JC, Beek PJ. Human Movement Science adopts Registered Reports for hypothesis-driven research. *Hum Mov Sci*. 2015;44:A1-A2.
125. Beilock SL, Carr TH. On the fragility of skilled performance: What governs choking under pressure? *J Exp Psychol*. 2001;130(4):701-725.
126. Plihal W, Born J. Effects of early and late nocturnal sleep on declarative and procedural memory. *J Cogn Neurosci*. 1997;9(4):534-547.
127. Ellmers TJ, Machado G, Wong TWL, Zhu F, Williams AM, Young WR. A validation of neural co-activation as a measure of attentional focus in a postural task. *Gait Posture*. 2016;50:229-231.

128. Miller MW, Rietschel JC, McDonald CG, Hatfield BD. A novel approach to the physiological measurement of mental workload. *Int J Psychophysiol*. 2011;80(1):75-78.
129. Button KS, Ioannidis JPA, Mokrysz C, et al. Power failure: why small sample size undermines the reliability of neuroscience. *Nat Rev Neurosci*. 2013;14(5):365-376.
130. Toner J, Montero BG, Moran A. Considering the role of cognitive control in expert performance. *Phenomenol Cogn Sci*. 2015;14(4):1127-1144.
131. Maurer H, Munzert J. Influence of attentional focus on skilled motor performance: Performance decrement under unfamiliar focus conditions. *Hum Mov Sci*. 2013;32(4):730-740.
132. Frensch P, Rünger D. Implicit learning. *Curr Dir Psychol Sci*. 2003;12:13-18.
133. Nys GMS, Van Zandvoort MJE, De Kort PLM, Jansen BPW, De Haan EHF, Kappelle LJ. Cognitive disorders in acute stroke: Prevalence and clinical determinants. *Cerebrovasc Dis*. 2007;23(5-6):408-416.
134. Kal E, Houdijk H, van der Wurff P, et al. The inclination for conscious motor control after stroke: Validating the Movement-Specific Reinvestment Scale for use in inpatient stroke patients. *Disabil Rehabil*. 2016;38(11):1097-1106.
135. Melby-Lervåg M, Hulme C, Melby-Lervag M, Hulme C. Is working memory training effective? A meta-analytic review. *Dev Psychol*. 2013;49(2):270-291.
136. Stanley J, Krakauer JW. Motor skill depends on knowledge of facts. *Front Hum Neurosci*. 2013;7.
137. Willingham DB. A neuropsychological theory of motor skill learning. *Psychol Rev*. 1998;105(3):558-584.
138. Sun R, Slusarz P, Terry C. The interaction of the explicit and the implicit in skill learning: A dual-process approach. *Psychol Rev*. 2005;112(1):159-192.
139. Hardy L, Mullen R, Jones G. Knowledge and conscious control of motor actions under stress. *Br J Psychol*. 1996;87(4):621-636.
140. Koedijker JM, Poolton JM, Maxwell JP, Oudejans RRD, Beek PJ, Masters RSW. Attention and time constraints in perceptual-motor learning and performance: Instruction, analogy, and skill level. *Conscious Cogn*. 2011;20(2):245-256.
141. Boyd LA, Winstein CJ. Impact of explicit information on implicit motor-sequence learning following middle cerebral artery stroke. *Phys Ther*. 2003;83(11):976-989.
142. 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(2):46-57.
143. Dovern A, Fink GR, Saliger J, Karbe H, Koch I, Weiss PH. Apraxia impairs intentional retrieval of incidentally acquired motor knowledge. *J Neurosci*. 2011;31(22):8102-8108.
144. Boyd LA, Winstein CJ. Providing explicit information disrupts implicit motor learning after basal ganglia stroke. *Learn Mem*. 2004;11(4):388-396.
145. Shin JC, Aparicio P, Ivry RB. Multidimensional sequence learning in patients with focal basal ganglia lesions. *Brain Cogn*. 2005;58(1):75-83.
146. Boyd LA, Winstein CJ. Cerebellar stroke impairs temporal but not spatial accuracy during implicit motor learning. *Neurorehabil Neural Repair*. 2004;18(3):134-143.
147. Gomez-Beldarrain M, Garcia-Monco JC, Rubio B, Pascual-Leone A. Effect of focal cerebellar lesions on procedural learning in the serial reaction time task. *Exp Brain Res*. 1998;120(1):25-30.
148. Boyd LA, Winstein CJ. Implicit motor-sequence learning in humans following unilateral stroke: The impact of practice and explicit knowledge. *Neurosci Lett*. 2001;298(1):65-69.
149. Vakil E, Kahan S, Huberman M, Osimani A. Motor and non-motor sequence learning in patients with basal ganglia lesions: The case of serial reaction time (SRT). *Neuropsychologia*. 2000;38(1):1-10.
150. Siegert RJ, Taylor KD, Weatherall M, Abernethy DA, David A. Is implicit sequence learning impaired in Parkinson ' s disease ? A meta-analysis. *Neuropsychology*. 2006;20(4):490-495.
151. Siegert RJ, Weatherall M, Bell EM. Is implicit sequence learning impaired in schizophrenia? A meta-analysis. *Brain Cogn*. 2008;67(3):351-359.
152. Wells GA, Shea B, O'Connell D, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomized studies in meta-analyses. The Ottawa Hospital Research Institute. http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp (last visited on September 15th, 2015).

153. Verwey WB, Clegg BA. Effector dependent sequence learning in the serial RT task. *Psychol Res*. 2005;69(4):242-251.
154. Bapi R, Doya K, Harner A. Evidence for effector independent and dependent representations and their differential time course of acquisition during motor sequence learning. *Exp Brain Res*. 2000;132(2):149-162.
155. Korman M, Raz N, Flash T, Karni A. Multiple shifts in the representation of a motor sequence during the acquisition of skilled performance. *Proc Natl Acad Sci*. 2003;100(21):12492-12497.
156. Whitehead A. *Meta-Analysis of Controlled Clinical Trials*. Chichester, UK: Wiley; 2002.
157. Bamford J, Sandercock P, Dennis M, Warlow C, Burn J. Classification and natural history of clinically identifiable subtypes of cerebral infarction. *Lancet*. 1991;337(8756):1521-1526.
158. Chang T, Tang P, Wu M, Tseng W, Jeng J, Chiu M. Role of frontostriatal fibers in motor sequence learning for patients with stroke and healthy adults. *Cerebrovasc Dis*. 2014;38:1-2.
159. Wadden K, Jones P, Borich M, Boyd L. Rate of motor sequence acquisition with contralesional glutamate concentrationi in chronic stroke. *Arch Phys Med Rehabil*. 2013;94:e29.
160. Lee M, Park R, Kwon Y, Park J, Jang S. Implicit motor sequence learning during serial reaction time tasks induced by visual feedback in patients with stroke. *J Kor Soc Phys Ther*. 2006;13:24-32.
161. Lee M, Park R, Nam K. The effect of implicit motor sequence learning through perceptual motor task in patients with subacute stroke. *J Kor Soc Phys Ther*. 2008;20:1-8.
162. Rösser N, Heuschmann P, Wersching H, Breitenstein C, Knecht S, Flöel A. Levodopa improves procedural motor learning in chronic stroke patients. *Arch Phys Med Rehabil*. 2008;89(9):1633-1641.
163. Boyd LA, Quaney BM, Pohl PS, Winstein CJ. Learning implicitly: Effects of task and severity after stroke. *Neurorehabil Neural Repair*. 2007;21(5):444-454.
164. Pohl P, McDowd J, Filion D, Richards L, Stiers W. Implicit learning of a motor skill after mild and moderate stroke. *Clin Rehabil*. 2006;20(3):246-253.
165. Boyd LA, Edwards JD, Siengsukon CS, Vidoni ED, Wessel BD, Linsdell MA. Motor sequence chunking is impaired by basal ganglia stroke. *Neurobiol Learn Mem*. 2009;92(1):35-44.
166. Dirnberger G, Novak J, Nasel C, Zehnter M. Separating coordinative and executive dysfunction in cerebellar patients during motor skill acquisition. *Neuropsychologia*. 2010;48(5):1200-1208.
167. Dirnberger G, Novak J, Nasel C. Perceptual sequence learning is more severely impaired than motor sequence learning in patients with chronic cerebellar stroke. *J Cogn Neurosci*. 2013;25(12):2207-2215.
168. Exner C, Koschack J. The differential role of premotor frontal cortex and basal ganglia in motor sequence learning: evidence from focal basal ganglia lesions. *Learn Mem*. 2002.
169. Orrell AJ, Orrell AJ, Eves FF, Masters RSW, MacMahon KMM. Implicit sequence learning processes after unilateral stroke. *Neuropsychol Rehabil*. 2007;17(3):335.
170. Pohl PS, McDowd JM, Filion DL, Richards LG, Stiers W. Implicit learning of a perceptual-motor skill after stroke. *Phys Ther*. 2001;81(11):1780-1789.
171. Meehan SK, Randhawa B, Wessel B, Boyd LA. Implicit sequence-specific motor learning after subcortical stroke is associated with increased prefrontal brain activations: An fMRI Study. *Hum Brain Mapp*. 2011;32(2):290-303.
172. Berry DC, Broadbent DE. Interactive tasks and the implicit-explicit distinction. *Br J Psychol*. 1988;79(2):251-272.
173. Kleynen M, Wilson MR, Jie LJ, te Lintel Hekkert F, Goodwin VA, Braun SM. Exploring the utility of analogies in motor learning after stroke: a feasibility study. *Int J Rehabil Res*. 2014;37(3):277-280.
174. Reisman DS, McLean H, Keller J, Danks KA, Bastian AJ. Repeated split-belt treadmill training improves poststroke step length asymmetry. *Neurorehabil Neural Repair*. 2013;27(5):460-468.
175. Savin DN, Morton SM, Whitall J. Generalization of improved step length symmetry from treadmill to overground walking in persons with stroke and hemiparesis. *Clin Neurophysiol*. 2014;125(5):1012-1020.
176. Deeks JJ, Dinnes J, D'Amico R, et al. Evaluating non-randomised intervention studies. *Health Technol Assess (Rockv)*. 2003;7(27):1-173.
177. Masters RSW, Polman RCJ, Hammond N V. "Reinvestment" : A dimension of personality implicated in skill dreakdown under pressure. *Pers Individ Dif*. 1993;14(5):655-666.
178. Johnson L, Burridge JH, Demain SH. Internal and external focus of attention during gait reeducation. *Phys Ther*. 2013;93(7):957-966.
179. Keppel CC, Crowe SF. Changes to body image and self-esteem following stroke in young adults. *Neuropsychol Rehabil*. 2000;10(1):15-31.

180. Wong WL, Masters RSW, Maxwell JP, Abernethy AB. Reinvestment and falls in community-dwelling older adults. *Neurorehabil Neural Repair*. 2015;22(4):410-414.
181. Masters RSW, Eves FF, Maxwell JP. Development of a movement specific reinvestment scale. In: *Proceedings of the ISSP 11th World Congress of Sport Psychology*. International Society of Sport Psychology (ISSP); 2005.
182. Kwakkel G, Kollen BJ. Predicting activities after stroke: What is clinically relevant? *Int J Stroke*. 2013;8(1):25-32.
183. Jørgensen HS, Nakayama H, Raaschou HO, Vive-Larsen J, Støier M, Olsen TS. Outcome and time course of recovery in stroke. Part II: Time course of recovery. The Copenhagen stroke study. *Arch Phys Med Rehabil*. 1995;76(5):406-412.
184. Jaeschke R, Guyatt GH. How to develop and validate a new quality of life instrument. In: Spiker B, ed. *Quality of Life Assessment in Clinical Trials.* 2nd ed. New York: Raven Press Ltd; 1990:49-56.
185. Field A. *Discovering Statistics. Using SPSS.* Vol 58. London: Sage; 2009.
186. Ling FCM, Maxwell J, Masters RSW, McManus AM, Polman RCJ. Psychometric properties of the movement-specific reinvestment scale for Chinese children. *Int J Sport Exerc Psychol*. 2016;14(3):227-239. d
187. Selfe J, Dey P, Richards J, et al. Do people who consciously attend to their movements have more self-reported knee pain? An exploratory cross-sectional study. *Clin Rehabil*. 2015;29(1):95-100.
188. Guillemin F, Bombardier C, Beaton D. Cross-cultural adaptation of health-related quality of life measures: Literature review and proposed guidelines. *J Clin Epidemiol*. 1993;46(12):1417-1432.
189. West SG, Finch JF, Curran PJ. Structural equation models with nonnormal variables: Problems and remedies. In: Hoyle RH, ed. *Structural Equation Modeling: Concepts, Issues and Applications*. Newbury Park, CA: Sage; 1995:56-75.
190. Jackson DL, Gillaspy Jr. JA, Purc-Stephenson R. Reporting practices in confirmatory factor analysis: An overview and some recommendations. *Psychol Methods*. 2009;14(1):6-23.
191. Hu LT, Bentler PM. Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Struct Equ Model*. 1999;6(1):1-55.
192. Medsker GJ, Williams LJ, Holahan PJ. A review of current practices for evaluating causal models in organizational behavior and human resources management research. *J Manage*. 1994;20(2):439-464.
193. Browne MW, Cudeck R. Alternative ways of assessing model fit. *Sociol Methods Res*. 1992;21(2):230-258.
194. Little TD, Slegers DW. Factor analysis: Multiple groups with means. In: Everitt B, Howell D, Rindskopf D (Section editor), eds. *Encyclopedia of Statistics in Behavioral Science*. Chichester, UK: Wiley; 2005:617-623.
195. Cheung GW, Rensvold RB. Evaluating goodness-of-fit indexes for testing measurement invariance. *Struct Equ Model*. 2002;9(2):233-255.
196. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL. International concensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported oucomes: Results of the COSMIN study. *J Clin Epidem*. 2010;63:737-745.
197. Coffman DL, Maydeu-Olivares A, Arnau J. Asymptotic distribution free interval estimation for an interclass correlation coefficient with applications to longitudinal data. *Methodology*. 2008;4(1):4-9.
198. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19(1):231-240.
199. de Vet HCW, Terwee CB, Knol DL, Bouter LM. When to use agreement versus reliability measures. *J Clin Epidemiol*. 2006;59(10):1033-1039.
200. Masters RSW, Pall HS, MacMahon KMA, Eves FF. Duration of Parkinson disease is associated with an increased propensity for “reinvestment.” *Neurorehabil Neural Repair*. 2007;21(2):123-126.
201. Laborde S, Dosseville F, Kinrade NP. Decision-specific reinvestment scale: An exploration of its construct validity, and association with stress and coping appraisals. *Psychol Sport Exerc*. 2014;15(3):238-246.
202. Stillman CM, Feldman H, Wambach CG, Howard JH, Howard D V. Dispositional mindfulness is associated with reduced implicit learning. *Conscious Cogn*. 2014;28(1):141-150. doi:10.1016/j.concog.2014.07.002.
203. Poolton J, Maxwell J, Masters R. Rules for reinvestment. *Percept Mot Ski*. 2004;99(3 Pt 1):771-774.
204. Abernethy B, Maxwell JP, Masters RSW, Van der Kamp J, Jackson RC. Attentional processes in skill learning and expert performance. In: Tenenbaum G, Eklund RC, eds. *Handbook of Sport Psychology*. 3rd ed. Hoboken, NJ: John Wiley & Sons; 2007:245-263.

205. Boisgontier MP, Beets IAM, Duysens J, Nieuwboer A, Krampe RT, Swinnen SP. Age-related differences in attentional cost associated with postural dual tasks: Increased recruitment of generic cognitive resources in older adults. *Neurosci Biobehav Rev*. 2013;37(8):1824-1837.
206. Kal E, van den Brink H, Houdijk H, et al. How physical therapists instruct patients with stroke: an observational study on attentional focus during gait rehabilitation after stroke. *Disabil Rehabil*. 2018;40(10):1154-1165.
207. Young WR, Olonilua M, Masters RSW, Dimitriadis S, Williams AM. Examining links between anxiety, reinvestment and walking when talking by older adults during adaptive gait. *Exp Brain Res*. 2016;234(1):161-172.
208. Chiviacowsky S, Wulf G, Wally R. An external focus of attention enhances balance learning in older adults. *Gait Posture*. 2010;32(4):572-575.
209. Fasoli SE, Trombly CA, Tickle-Degnen L, Verfaellie MH. Effect of instructions on functional reach in persons with and without cerebrovascular accident. *Am J Occup Ther*. 2002;56(4):380-390.
210. Muckel S, Mehrholz J. Immediate effects of two attention strategies on trunk control on patients after stroke. A randomized controlled pilot trial. *Clin Rehabil*. 2014;28(7):632-636.
211. Durham K, Sackley CM, Wright CC, Wing AM, Edwards MG, Van Vliet P. Attentional focus of feedback for improving performance of reach-to-grasp after stroke: a randomised crossover study. *Physiotherapy*. 2014;10:108-115.
212. Kal EC, van der Kamp J, Houdijk H, Groet E, van Bennekom CAM, Scherder EJA. Stay focused! The effects of internal and external focus of attention on movement automaticity in patients with stroke. *PLoS One*. 2015;10(8):e0136917.
213. Kim GJ, Hinojosa J, Rao AK, Batavia M, O'Dell MW. A randomized trial on the effects of attentional focus on motor training of the upper extremity using robotics with individuals after chronic stroke. *Arch Phys Med Rehabil*. 2017;98(10):1924-1931.
214. Tse ACY, van Ginneken WF. Children's conscious control propensity moderates the role of attentional focus in motor skill acquisition. *Psychol Sport Exerc*. 2017;31:35-39.
215. Maurer H, Munzert J. Influence of attentional focus on skilled motor performance: Performance decrement under unfamiliar focus conditions. *Hum Mov Sci*. 2013;32(4):730-740.
216. Beilock SL, Bertenthal BI, McCoy AM, Carr TH. Haste does not always make waste: expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychon Bull Rev*. 2004;11(2):373-379. http://www.embase.com/search/results?subaction=viewrecord&from=export&id=L39290907.
217. Perkins-Ceccato N, Passmore SR, Lee TD. Effects of focus of attention depend on golfers' skill. *J Sports Sci*. 2003;21(8):593-600.
218. Hofheinz M, Schusterschitz C. Dual task interference in estimating the risk of falls and measuring change: A comparative, psychometric study of four measurements. *Clin Rehabil*. 2010;24(9):831-842. doi:10.1177/0269215510367993.
219. Podsiadlo D, Richardson S. The timed "Up and Go": A test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc*. 1991;39(2):142-148.
220. Kal E, Houdijk H, van der Kamp J, et al. Are the effects of internal focus instructions different from external focus instructions given during balance training in stroke patients? A double-blind randomized controlled trial. *Clin Rehabil*. 2018;Early onli:26921551879524.
221. Uiga L, Capio CM, Wong TWL, Wilson MR, Masters RSW. Movement specific reinvestment and allocation of attention by older adults during walking. *Cogn Process*. 2015;16:421-424.
222. Yang L, He C, Pang MYC. Reliability and validity of dual-task mobility assessments in people with chronic stroke. *PLoS One*. 2016;11(1).
223. Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Phys Ther*. 2000;80:896-903. doi:N/A.
224. Flansbjer UB, Holmbäck AM, Downham D, Patten C, Lexell J. Reliability of gait performance tests in men and women with hemiparesis after stroke. *J Rehabil Med*. 2005;37(2):75-82.
225. Collen FM, Wade DT, Bradshaw CM. Mobility after stroke: Reliability of measures of impairment and disability. *Disabil Rehabil*. 1990;12(1):6-9.

226. Wolf SL, Catlin P, Gage K, Gurucharri K, Robertson R, Stephen K. Establishing the reliability and validity of measurements of walking time using the Emory Functional Ambulation Profile. *Phys Ther*. 1999;79(12):1122-1133.
227. Verhage F. Intelligence and age in a dutch sample. *Hum Dev*. 1965;8(4):238-245.
228. Wechsler D. *Manual for the Wechsler Adult Intelligence Scale - Revised*.; 1981.
229. D'Elia LF, Satz P, Uchiyama CL, White T. *Color Trails Test: Professional Manual*. FL: Odessa; 1996.
230. Brinckenkamp R, Oosterveld P. *De d2 Aandachts- En Concentratietest, Nederlandse Bewerking van de "Aufmerksamheits Belastung Test" van R. Brinckenkamp*. Amsterdam: Hogrefe Publishing; 2007.
231. Stolk-Hornsveld F, Crow JL, Hendriks EP, van der Baan R, Harmeling-van der Wel BC. The Erasmus MC modifications to the (revised) Nottingham Sensory Assessment: a reliable somatosensory assessment measure for patients with intracranial disorders. *Clin Rehabil*. 2006;20(2):160-172.
232. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: Validation of an instrument. In: *Canadian Journal of Public Health*. Vol 83. ; 1992.
233. Post MW, van de Port IG, Kap B, Berdenis van Berlekom SH. Development and validation of the Utrecht Scale for Evaluation of Clinical Rehabilitation (USER). *Clin Rehabil*. 2009;23:909-917.
234. Charlson M, Szatrowski TP, Peterson J, Gold J. Validation of a combined comorbidity index. *J Clin Epidemiol*. 1994;47(11):1245-1251.
235. Holden MK, Gill KM, Magliozzi MR, Nathan J, Piehl-Baker L. Clinical gait assessment in the neurologically impaired. Reliability and meaningfulness. *Phys Ther*. 1984;64(1):35-40.
236. Smulders K, van Swigchem R, de Swart BJM, Geurts ACH, Weerdesteyn V. Community-dwelling people with chronic stroke need disproportionate attention while walking and negotiating obstacles. *Gait Posture*. 2012;36(1):127-132.
237. Holm S. A simple sequentially rejective multiple test procedure. *Scand J Stat*. 1979;6:65-70.
238. de Melker Worms JLA, Stins JF, van Wegen EEH, Loram ID, Beek PJ. Influence of focus of attention, reinvestment and fall history on elderly gait stability. *Physiol Rep*. 2017;5(1):e13061.
239. Malhotra N, Poolton JM, Wilson MR, Uiga L, Masters RSW. Examining Movement-Specific Reinvestment and Performance in Demanding Contexts. *J Sport Exerc Psychol*. 2015;37(3):327-338.
240. van Ginneken WF, Poolton JM, Masters RSW, Capio CM, Kal EC, van der Kamp J. Comparing the effects of conscious monitoring and conscious control on motor performance. *Psychol Sport Exerc*. 2017;30:145-152.
241. Dickey L, Kagan A, Lindsay MP, Fang J, Rowland A, Black S. Incidence and profile of inpatient stroke-induced aphasia in Ontario, Canada. *Arch Phys Med Rehabil*. 2010;91(2):196-202.
242. Collins D, Carson HJ, Toner J. Letter to the editor concerning the article "Performance of gymnastics skill benefits from an external focus of attention" by Abdollahipour, Wulf, Psotta & Nieto (2015). *J Sports Sci*. 2016;34(13):1288-1292.
243. UNESCO. *ISCED 1997 - International Standard Classification of Education*. Vol 54.; 2006. http://www.unesco.org/education/information/nfsunesco/doc/isced_1997.htm.
244. Mehrholz J, Wagner K, Rutte K, Meißner D, Pohl M. Predictive validity and responsiveness of the Functional Ambulation Category in hemiparetic patients after stroke. *Arch Phys Med Rehabil*. 2007;88(10):1314-1319.
245. Roorda LD, Green J, De Kluis KRA, et al. Excellent cross-cultural validity, intra-test reliability and construct validity of the Dutch Rivermead Mobility Index in patients after stroke undergoing rehabilitation. *J Rehabil Med*. 2008;40(9):727-732.
246. Tyson S, Connell L. The psychometric properties and clinical utility of measures of walking and mobility in neurological conditions: A systematic review. *Clin Rehabil*. 2009;23(11):1018-1033.
247. Nasreddine ZS, Phillips NA, Bédirian V, et al. The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*. 2005;53(4):695-699.
248. Bowerman BL, O'Connell RT. *Linear Statistical Models: An Applied Approach*. 2nd ed. Belmont, CA, US: Duxbury; 1990.
249. Myers R. *Classical and Modern Regression with Applications*. 2nd ed. Boston, MA: Duxbury; 1990.
250. Durbin J, Watson GS. Testing for serial correlation in least squares regression. II. *Biometrika*. 1951;30:159-178.
251. Peppen R van, Kwakkel G, Harmeling-van der Wel B, Kollen B, Hobbelen J, Buurke J. KNGF Clinical Practice Guideline for physical therapy in patients with stroke. Review of the evidence. *Ned Tijdschr voor Fysiother*. 2004;114(5).

252. Wulf G, Prinz W. Directing attention to movement effects enhances learning: A review. *Psychon Bull Rev*. 2001;8(4):648-660.
253. Wulf G. *Attention and Motor Skill Learning*. Champaign, IL, US: Human Kinetics; 2007.
254. McNevin N, Shea C, Wulf G. Increasing the distance of an external focus of attention enhances learning. *Psychol Res - Psychol Forsch*. 2003;67:22-29.
255. Zachry T, Wulf G, Mercer J, Bezodis N. Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Res Bull*. 2005;67(4):304-309.
256. Shea CH, Wulf G. Enhancing motor learning through external-focus instructions and feedback. *Hum Mov Sci*. 1999;18(4):553-571.
257. Maddox MD, Wulf G, Wright DL. The effect of an internal vs. external focus of attention on the learning of a tennis stroke. *J Excercise Psychol*. 1999;21:S78.
258. Wulf G, Dufek JS, Lozano L, Pettigrew C. Increased jump height and reduced EMG activity with an external focus. *Hum Mov Sci*. 2010;29(3):440-448.
259. Canning CG. The effect of directing attention during walking under dual-task conditions in Parkinson's disease. *Park Relat Disord*. 2005;11(2):95-99.
260. Shemmell JB, Forner MM, Tresilian JR, Riek S, Barry BK, Carson RG. Neuromuscular adaptation during skill acquisition on a two degree-of-freedom target acquisition task: Isometric torque production. *J Neurophysiol*. 2005;94(5):3058-3068.
261. Roerdink M, Hlavackova P, Vuillerme N. Center-of-pressure regularity as a marker for attentional investment in postural control: A comparison between sitting and standing postures. *Hum Mov Sci*. 2011;30:203-212.
262. Hreljac A. Stride smoothness evaluation of runners and other athletes. *Gait Posture*. 2000;11(3):199-206.
263. Thomas JR, Yan JH, Stelmach GE. Movement substructures change as a function of practice in children and adults. *J Exp Child Psychol*. 2000;75(3):228-244.
264. Hogan N, Sternad D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. *J Mot Behav*. 2009;41(6):529-534.
265. Flash T, Hogan N. The coordination of arm movements: An experimentally confirmed mathematical model. *J Neurosci*. 1985;5(7):1688-1703. doi:4020415.
266. Hogan N. An organizing principle for a class of voluntary movements. *J Neurosci*. 1984;4(11):2745-2754.
267. Richman JS, Moorman JR. Physiological time-series analysis using approximate entropy and sample entropy. *Am J Physiol*. 2000;278:H2039-H2049.
268. Lamoth CJC, van Lummel RC, Beek PJ. Athletic skill level is reflected in body sway: A test case for accelometry in combination with stochastic dynamics. *Gait Posture*. 2009;29(4):546-551. doi:10.1016/j.gaitpost.2008.12.006.
269. Vaillancourt DE, Sosnoff JJ, Newell KM. Age-related changes in complexity depend on task dynamics. *J Appl Physiol*. 2004;97:454-455.
270. Vaillancourt DE, Newell KM. Changing complexity in human behavior and physiology through aging and disease. *Neurobiol Aging*. 2002;23(1):1–11.
271. Newell KM, Broderick MP, Deutsch KM, Slifkin AB. Task goals and change in dynamical degrees of freedom with motor learning. *J Exp Psychol Hum Percept Perform*. 2003;29(2):379-387.
272. Schmand B, Groenink SC, van den Dungen M. Letter fluency: psychometric properties and Dutch normative data. *Tijdschr Gerontol Geriatr*. 2008;39:64-76.
273. Elias LJ, Bryden MP, Bulman-Fleming MB. Footedness is a better predictor than is handedness of emotional lateralization. *Neuropsychologia*. 1998;36(1):37-43.
274. H.J. Hermens, B Freriks. SENIAM Project. The SENIAM project. http://www.seniam.org/. Published 2017.
275. Bohannon RW. Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants. *Age Ageing*. 1997;26(1):15-19.
276. Lake DE, Richman JS, Griffin MP, Moorman JR. Sample entropy analysis of neonatal heart rate variability. *Am J Physiol - Regul Integr Comp Physiol*. 2002;283(3):R789-R797.
277. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, New Jersey: Lawrence Erlbaum; 1988.
278. Cohen J. Quantitative methods in psychology: A power primer. *Psychol Bull*. 1992;112(1):155-159.
279. McCulloch KL, Buxton E, Hackney J, Lowers S. Balance, attention, and dual-task performance during walking after brain Injury: Associations with falls history. *J Head Trauma Rehabil*. 2010;25(3):155-163.

280. Lohse KR, Sherwood DE. Thinking about muscles: The neuromuscular effects of attentional focus on accuracy and fatigue. *Acta Psychol*. 2012;140(3):236-245.
281. Hossner EJ, Ehrlenspiel F. Time-referenced effects of an internal vs. external focus of attention on muscular activity and compensatory variability. *Front Psychol*. 2010;1:230.
282. Lohse KR, Sherwood DE, Healy AF. Neuromuscular effects of shifting the focus of attention in a simple force production task. *J Mot Behav*. 2011;43(2):173-184.
283. Zentgraf K, Lorey B, Bischoff M, Zimmermann K, Stark R, Munzert J. Neural correlates of attentional focusing during finger movements: A fMRI study. *J Mot Behav*. 2009;41(6):535-541.
284. Jueptner M, Stephan KM, Frith CD, Brooks DJ, Frackowiak RS, Passingham RE. Anatomy of motor learning. I. Frontal cortex and attention to action. *J Neurophysiol*. 1997;77(3):1313-1324.
285. Hatfield BD, Haufler AJ, Hung TM, Spalding TW. Electroencephalographic studies of skilled psychomotor performance. *J Clin Neurophysiol*. 2004;21(3):144-156.
286. Beilock SL, Carr TH, MacMahon C, Starkes JL. When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *J Exp Psychol Appl*. 2002;8(1):6-16.
287. Hyndman D, Ashburn A. "Stops walking when talking" as a predictor of falls in people with stroke living in the community. *J Neurol Neurosurg Psychiatry*. 2004;75(7):994-997.
288. Vance J, Wulf G, Töllner T, McNevin N, Mercer J. EMG activity as a function of the performer's focus of attention. *J Mot Behav*. 2004;36(4):450-459.
289. Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Repair*. 2007;21(5):398-411.
290. Kok R, Verhey F. Dutch translation of the Mini-Mental State Examination. (Folstein et al.,1975). 2002.
291. Al-Yahya E, Dawes H, Smith L, Dennis A, Howells K, Cockburn J. Cognitive motor interference while walking: A systematic review and meta-analysis. *Neurosci Biobehav Rev*. 2011;35(3):715-728.
292. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. *Scand J Rehabil Med*. 1975;7:13-31.
293. Demeurisse G, Demol O, Robaye E. Motor evaluation in vascular hemiplegia. *Eur Neurol*. 1980;19(6):382-389.
294. Malhotra N, Poolton JM, Wilson MR, Omuro S, Masters RSW. Dimensions of movement specific reinvestment in practice of a golf putting task. *Psychol Sport Exerc*. 2015;18:1-8.
295. Delis DC, Kaplan E, Kramer JH. *Delis-Kaplan Executive Function System (D-KEFS) – Nederlandstalige Bewerking*. Amsterdam: Pearson Assessment and Information B.V; 2007.
296. Culbertson W, Zillmer EA. *TOL – DX Tower of London – Drexel University*. 2nd ed. Toronto: Multi-Health Systems; 2005.
297. Wechsler D. *WAIS-III – Nederlandstalige Bewerking. Afname En Scoringshandleiding*. Lisse: Swets & Zeitlinger; 2005.
298. Wechsler D. *WAIS-IV - Nederlandstalige Bewerking*. Amsterdam: Pearson Assessment and Information B.V; 2012.
299. Weiss SM, Reber AS, Owen DR. The locus of focus: The effect of switching from a preferred to a non-preferred focus of attention. *J Sports Sci*. 2008;26(10):1049-1057.
300. Beilock SL, Carr TH. On the fragility of skilled performance: What governs choking under pressure? *J Exp Psychol Gen*. 2001;130(4):701-725.
301. Huxhold O, Li SC, Schmiedek F, Lindenberger U. Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Res Bull*. 2006;69(3):294-305.
302. Zachry T, Wulf G, Mercer J, Bezodis N. Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Res Bull*. 2005;67(4):304-309.
303. Verhage F. Intelligentie en leeftijd: onderzoek bij Nederlanders van twaalf tot zevenzeventig jaar [Intelligence and Age: study with Dutch people aged 12 to 77]. *Assen Van Gorcum*. 1964.
304. Wechsler D. *Wechsler Memory Scale - Revised*. New York, NY, USA: The Psychological Corporation; 1987.
305. Brouwer R, Kal E, van der Kamp J, Houdijk H. Validation of the stabilometer balance test: Bridging the gap between clinical and research based balance control assessments for stroke patients. *Gait Posture*. 2018; In press.
306. Mercer VS, Freburger JK, Chang S-H, Purser JL. Measurement of paretic-lower-extremity loading and weight transfer after stroke. *Phys Ther*. 2009;89(7):653-664. d

307. Cheng PT, Liaw MY, Wong MK, Tang FT, Lee MY, Lin PS. The sit-to-stand movement in stroke patients and its correlation with falling. *Arch Phys Med Rehabil*. 1998;79(9):1043-1046.
308. Cheng PT, Wu SH, Liaw MY, Wong AMK, Tang FT. Symmetrical body-weight distribution training in stroke patients and its effect on fall prevention. *Arch Phys Med Rehabil*. 2001;82(12):1650-1654.
309. Karmali F, Chaudhuri SE, Yi Y, Merfeld DM. Determining thresholds using adaptive procedures and psychometric fits: evaluating efficiency using theory, simulations, and human experiments. *Exp Brain Res*. 2016;234(3):773-789.
310. Taylor MM, Creelman CD. PEST: Efficient Estimates on Probability Functions. *J Acoust Soc Am*. 1967;41(4):782-787.
311. White IR, Horton NJ, Carpenter J, Pocock SJ. Strategy for intention to treat analysis in randomised trials with missing outcome data. *BMJ*. 2011;342:d40.
312. Deci EL, Ryan RM. Self-determination theory: A macrotheory of human motivation, development, and health. *Can Psychol*. 2008;49(3):182-185.
313. Sakurada T, Nakajima T, Morita M, Hirai M, Watanabe E. Improved motor performance in patients with acute stroke using the optimal individual attentional strategy. *Sci Rep*. 2017;7.
314. Kal E, Prosée R, Winters M, van der Kamp J. Does implicit motor learning lead to greater automatization of motor skills compared to explicit motor learning? A systematic review. *PLoS One*. 2018;13(9):e0203591.
315. Kleynen M, Braun SM, Rasquin SMC, et al. Multidisciplinary views on applying explicit and implicit motor learning in practice: An international survey. *PLoS One*. 2015.
316. Castaneda B, Gray R. Effects of focus of attention on baseball batting performance in players of differing skill levels. *J Sport Exerc Psychol*. 2007;29(1):60-77.
317. Beilock SL, Carr TH, MacMahon C, Starkes JL. When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *J Exp Psychol*. 2002;8(1):6-16.
318. Marchant DC, Clough PJ, Crawshaw M, Levy A. Novice motor skill performance and task experience is influenced by attentional focusing instructions and instruction preferences. *Int J Sport Exerc Psychol*. 2009;7(4):488-502.
319. van Abswoude F, Santos-Vieira B, van der Kamp J, Steenbergen B. The influence of errors during practice on motor learning in young individuals with cerebral palsy. *Res Dev Disabil*. 2015;45-46:353-364.
320. Cole J. *Pride and a Daily Marathon*. Cambridge, MA, US / London: MIT Press; 1995.
321. Cole J, Paillard J. Living without Touch and Peripheral Information about Body Position and Movement : Studies with Deafferented Subjects. In: Bermúdez J, Marcel A, Eilan N, eds. *The Body and the Self*. Cambridge, MA, US / London: MIT Press; 1995:246-266.
322. Toner J, Moran A. Enhancing performance proficiency at the expert level: Considering the role of "somaesthetic awareness." *Psychol Sport Exerc*. 2015;16:110-117.
323. Shusterman R. Body consciousness and performance: Somaesthetics east and west. *J Aesthet Art Crit*. 2009;67(2):133-145.
324. Vidoni ED, Boyd LA. Preserved motor learning after stroke is related to the degree of proprioceptive deficit. *Behav Brain Funct*. 2009;5(1):36. d
325. van Abswoude F et al. Individual differences influencing immediate effects of internal and external focus instructions on children's motor performance. *Res Q Exerc Sport*.
326. Dreyfus HL, Dreyfus SE. From Socrates to expert systems. The limits of calculative rationality. *Technol Soc*. 1984;6(3):217-233.
327. Kramer AF, Larish JL. Aging and dual-task performance. In: Rogers WA, Fisk AD, Walker N, eds. *Aging and Skilled Performance: Advances in Theory and Applications.* Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc; 1996:83-112.
328. Silsupadol P, Shumway-Cook A, Lugade V, et al. Effects of single-task versus dual-task training on balance performance in older adults: a double-blind, randomized controlled trial. *Arch Phys Med Rehabil*. 2009;(3):381-387.
329. Jie L-J, Kleynen M, Meijer K, Beurskens A, Braun S. The effects of implicit and explicit motor learning in gait rehabilitation of people after stroke: Protocol for a randomized controlled trial. *JMIR Res Protoc*. 2018;7(5):e142.
330. Beatty J. Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychol Bull*. 1982;91(2):276-292.

331. Beatty J, Kahneman D. Pupillary changes in two memory tasks. *Psychon Sci*. 1966;5(10):371-372.
332. Kal E, Kragting B, Detillon N, Koelewijn T, van der Kamp J. Pupil dilation as an indicator of mental effort during a balance task - Proof of concept. Manuscript in preparation.
333. Al-Yahya E, Dawes H, Smith L, Dennis A, Howells K, Cockburn J. Cognitive motor interference while walking: A systematic review and meta-analysis. *Neurosci Biobehav Rev*. 2011;35(3):715-728.

Amsterdam Movement Sciences

Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.